ADVANCED CONSTRUCTION TECHNOLOGY RESEARCH

FINAL REPORT

Final Report to the
U.S. Army Research Office
for
Research Contract No. DAAL03-87-K-0006

ADVANCED CONSTRUCTION TECHNOLOGY CENTER
UNIVERSITY of ILLINOIS at URBANA-CHAMPAIGN
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13. ABSTRACT *(Maximum 200 words)*

The research reported was part of the Department of Defense Universities Research Initiative (URI) Program. Because of the heavy investment in planning, design, construction, maintenance, and operation of its huge physical plant, the U.S. Army included Advanced Construction Technology as one of the areas of concentration in the URI program. The research program reported here consisted of 28 research projects conducted in the following five thrust areas: nondestructive evaluation technologies for constructed works, construction site metrology, new materials and material technologies for construction, computer-aided construction, and special technologies. Accordingly, the research program was a multi-disciplinary program conducted by faculty and graduate students at the University of Illinois.

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ADVANCED CONSTRUCTION TECHNOLOGY CENTER
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
URBANA, ILLINOIS

ACKNOWLEDGEMENTS

This report is a summary of the research as conducted under the auspices of the U.S. Army Research Office as part of the Department of Defence University Research Initiative Program. The research was conducted during the period 1986 - 1993 by faculty and graduate students of the University of Illinois at Urbana-Champaign. There were many individuals who made important contributions to the work and these are gratefully acknowledged. Dr. Robert Singleton, Dr. Fritz Oertel, and Dr. Gary Anderson of the Army Research Office administered the program and their contributions were important to the program's success.

Throughout the work, the program was guided by an Army Advisory Committee who advised on areas of importance for research, reviewed progress, and assisted with coordination of the research program with activities in appropriate Department of Defence laboratories. Members of this committee are as follows.

Dr. L.R. Shaffer, U.S. Army Construction Engineering Research Laboratory, Champaign, Illinois (Committee Chairman)
Dr. Eugene Marvin, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire
Dr. Margaret E. Roylance, U. S. Army Materials Technology Laboratory, Watertown, Massachusetts
Dr. Robert Storer, Naval Civil Engineering Laboratory, Port Hueneme, California
Dr. Lillian D. Wakeley, Waterways Experiment Station, Vicksburg, Mississippi
Dr. Dean Norman, Waterways Experiment Station, Vicksburg, Mississippi
Dr. Giuliano D'Andrea, Benet Weapons Laboratory, Watervliet Arsenal, Watervliet, New York
Dr. Michael Katona, HQ Air Force Engineering and Services Center, U.S. Air Force Base, Tyndall, Florida
Dr. Spencer T. Wu, Air Force Office of Scientific Research, Bolling Air Force Base, Washington, D.C.

All of these were generous in their assistance. A note of special thanks is for Dr. L.R. Shaffer who served as Chairman. He was especially active in assisting with the definition of research areas objectives and matters of coordination with the DoD labs. In addition to the official advisory committee, a small group of industry representatives also served as advisors to the program including Mr. Frank H. Thomas of Turner Construction Company, Mr. Robert Tudhope of O'Neil Construction Company, and Mr. Richard P. Tuetken and Mr. Daniel L. Shamblin of Commonwealth Edison Company and their assistance is greatly acknowledged.

Finally, many University of Illinois Staff members made many important contributions to the program. First among these are the faculty and graduate students who were responsible for the research program. They are named in the part of this report describing their research.

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INTRODUCTION

This report is the summary of the research conducted under the auspices of the U.S. Army Research Office by the Advanced Construction Technology Center under Contract No. DAAL03-87-K-0006.

The work was part of the Department of Defence University Research Initiative (URI). The overall objective of the URI program was to provide for basic research directed to important needs of the Department of Defence, to encourage advanced training for students in strategic areas of importance to future national defence, to assist universities in the acquisition of modern laboratory equipment, and to encourage cooperation between university researchers and their counterparts in government laboratories.

The U.S. construction industry is of great importance to the U.S. Army. The U.S. Army owns approximately $175 billion dollars worth of facilities located in over 200 major installations worldwide. These installations consist of over 12.5 million acres of real estate. The U.S. Army owns over 390,000 miles of paved surfaces, 27,000 miles of utility lines, and 1.8 billion square feet of building space. The average age of the U.S. Army's physical facilities is well over thirty years old, and over thirty percent of the facilities are obsolete. A critical part of the U.S. Army's strategy (to modernize facilities) is to encourage appropriate research and development to reduce annual costs of repair and maintenance as well as new construction of facilities. In FY87, the Army spent over four billion dollars in operating and maintaining its installation infrastructure. Approximately six percent of the Army budget in FY87 was spent on maintenance, repair, and engineering services in support of installation operation. Accordingly, the Army concluded that its infrastructure funds must become more productive. This translates into the necessity to help improve the productivity of the U.S. construction industry as a whole. This is true because eighty-five percent of the design and one-hundred percent of the construction of Army facilities are performed by the U.S. construction industry under contract. Currently, the productivity of the U.S. construction industry has a direct impact on the ability of the Army to provide facilities needed to perform its missions.

By the middle part of the decade of the 1980s, it was generally accepted that the U.S. construction industry had, if not declining, at least stagnant levels of productivity. This was manifested by increasing construction costs, decline of U.S. construction industry share of international construction, and the entry of foreign construction companies into the U.S. domestic market. The Bureau of Labor Statistics has documented the alarming drop in the productivity of the U.S. construction industry subsequent to 1969. Though all causes are not fully understood, it is generally accepted that one important cause is the failure to revitalize the technology base of the industry. One important factor in the productivity improvement from 1947 to 1970 in the construction industry is thought to be improved automation of labor-intensive field tasks such as earth moving, concrete pouring, heavy lift operations, etc. Progress in the technological base was made possible by the long-term stable construction markets during this time period. Basically, the construction industry during this period was able to improve products and make advances using technology during World War II.

In view of this strategy, the Army chose to include advanced construction technology as an element of the URI program. The University of Illinois was one of the institutions selected to develop a program of excellence in multi-disciplinary research focused on

adapting new emerging technologies to the needs of the construction industry. It was required that the research be basic, rather than research applied to the development of specific products. In response to this challenge, the University of Illinois developed the broad interdisciplinary program which encompassed five thrust areas related to construction. These included nondestructive evaluation technologies for constructed works, construction site metrology, new materials and technologies for construction, computer-aided construction, and special technologies. A short overview of each of these thrust areas is given below.

Nondestructive evaluation technologies for constructed works (NDE). Nondestructive test and evaluation methods are necessary for quality assurance and control of manufactured construction components/materials, automation of the construction process itself, improved management and maintenance of constructed works, and lower costs of maintenance and repair. Research topics were selected to emphasize the importance of both on-site evaluation of constructed works and remote sensing and remaining life-time determinations.

Examples of research include force dynamic response monitoring for NDE damage in structures, electromagnetic sensing of concrete, accelerated test for soil properties, masonry building NDE, one-line displacement monitoring for measuring residual stresses, scattering of electromagnetic and acoustic waves by objects and voids within concrete structures, optical fiber strain sensors for smart structures, computer vision techniques for NDE of structural damage, and new methods to reduce computational effort in structural dynamics calculations.

Construction site metrology. The goal is to develop basic methods to collect, interpret, and analyze three-dimensional metric data in a fully automated mode and, possibly, in real time. Data types include point positions, distances, directions, volumes, areas, and surface shapes and geometries. The ability to collect and analyze the data types on a timely basis and without human involvement is essential to the automation of many construction processes, including terrain mapping, site layout, process control and verification, inspection, as-built survey, inventory, robot guidance, and monitoring structural and ground motion.

New material and material technologies for construction. The use of advanced materials for construction offers a particularly attractive means for improving the productivity and technological capability of the construction industry. Advanced materials are light, strong, tough, and durable and can be made into finished components using automated production techniques. In addition, the mechanical properties of advanced polymeric and ceramic materials can be engineered to provide high performance in this constructed works environment.

Research has focused on advanced ceramics for building construction, high-performance cementitious materials, concepts for lightweight energy-efficient building materials, ion-plated coatings for electromagnetic pulse and electromagnetic interference applications, and coatings that resist corrosion.

Computer-aided construction. Computers and advanced information techniques can be applied to all phases of the construction process. Artificial intelligence and knowledge-based systems can more efficiently coordinate job phases, reduce design error, and provide more timely and useful information to support decision. They will accelerate automation on the job site. Additionally, computers can provide interactive analytical and simulation environments, which can enhance and accelerate design verification and consideration of issues about construction possibilities during the design phase of a project.

Research is directed to such topics as developing a basic framework and software for cooperative decision making by engineering team members during various life-cycle phases, automatic synthesis of design from requirements generated by various sources, object-oriented models for integrating design and construction, handling constraints in object-oriented databases, automated conformance checking of designs with code requirements, design for automated construction, and expert systems for improved life-cycle engineering for facilities.

Special technologies. There are areas of special interest to the army that fall outside of the four areas described above. For example, recent laboratory research has identified the potential application of electroabsorption in a single quantum well heterostructure laser for the implementation of an optically based electric and/or magnetic field sensor. The semiconductor device, whose light transmission properties change with applied bias, would be part of a sensor system used to measure the fields produced in electromagnetic pulse simulations of protective constructions. In a laboratory setting, the new device has demonstrated high sensitivity and good time response required for accurate field measurements.

Another example is the study of *in-situ* soil reinforcement technology, or "soil nailing," through an integrated approach using analytical models, very large scale laboratory models, and observation from field installations.

During the performance of the research, we carried on a total number of twenty-eight projects were conducted in these five thrust areas. In the remainder of this report, each separate research project cyonducted by the Center is described, and the reports are grouped according to the thrust area in which the program was conducted.

THRUST AREA

NONDESTRUCTIVE EVALUATION (NDE) TECHNOLOGIES FOR CONSTRUCTED WORKS

USE OF COMPUTER VISION TECHNIQUES IN NDE OF STRUCTURAL DAMAGE
(Project No. 19)

by

T.S. Huang, Professor of Electrical and Computer Engineering

PROBLEM STUDIED:

A promising method of detecting and assessing damage in large structures (such as buildings, railroads, and bridges) is to load the structure statically or dynamically and measure its response. Damage is then inferred from the response. Current techniques involve the attachment of mechanical sensors (accelerometers) to the structure, which could be awkward and time-consuming.

The main goal of our research is to develop techniques of static and dynamic response measurement which are based on nontouching visual sensors (2D and 1D CCD arrays) and image analysis. Specific issues which need investigation include: type, number and locations of sensors needed for various scenarios; sensor cooperation; and spatial and temporal resolution and accuracy requirements.

Clearly, the answers to questions related to the above issues are closely couples with how damage is inferred from the response. Thus, we are also interested in the latter problem. In particular, we use the indirect approach of K. Hjelmstad, UIUC, where structural parameters such as stiffness are first estimated from the response, as well as look into the possibility of assessing damage directly from the measured response.

SUMMARY OF MOST IMPORTANT RESULTS:

This research project aims at generating new technologies for nondestructive evaluation of structural damage which are more economical and/or faster than existing ones. The approach is based on the use of visual sensing and computer vision techniques.

The structure under study is loaded statically or dynamically, and the locations and/or movements of point and edge features on the structure are measured by CCD cameras. Then damage is inferred from the measured data. We investigate issues related to the type, number, and locations of sensors needed for various scenarios; sensor cooperation; and spatial and temporal resolution and accuracy requirements. We summarize below our major results:

Accuracy of target location estimated from CCD TV camera images. We have designed and carried out a laboratory experiment using stereo to measure the locations of feature points and edges on a simple frame under static loading. The goal of the experiment is to make an assessment of the spatial/temporal resolution and accuracy achievable by visual sensing.

In this experiment, a pair of CCD cameras were used to measure the static displacements in a two story, single tier aluminum frame model. The cameras were carefully calibrated. Measurements with this setup are accurate to within 0.1 pixel in a 512 $\times$ 512 image. From a pair of stereo images of the undeflected frame, we estimated the 3D

locations of the nodes using a subpixel estimation algorithm. Next we statically deflected the frame and repeated the procedure to estimate the displacement of each node. We repeated the experiment for various loads. The actual displacement and load force in each case was physically measured using vernier calipers. To analyze the structure, we used a finite element analysis program in which each frame element was modeled as a 2D Bernoulli-Euler beam element — an isotropic, linearly elastic beam with uniform rectangular cross-section and negligible axial and shear deformation. We chose this model since the beams were rather long, flat, and thin, and experienced relatively small deformations. Using nodal displacement measurements, we attained an average flexural stiffness estimation error of 2.35 percent.

Under small static deformations, the deflected curve of each beam is described by a third order polynomial parameterized by *EI*, the flexural stiffness of the beam. This *a priori* knowledge of beam shape motivates us to take measurements along the entire length of each beam, since if we can recover the shape of each beam, we can compute the stiffness. The problem with using two cameras is that when a beam lies roughly parallel to the epipolar plane, we cannot reliably match points on the beam. This led us to consider the use of three or more cameras, and arrangement that could measure the shape of beams oriented in any direction. From experiments, we have found the three cameras provide a measurement accuracy of 0.05 pixels.

Robust algorithms for motion estimation. It has been the experience of researchers in computer vision that most algorithms for 3D motion estimation (from 2D image sequences) are quite sensitive to noise. Thus, we have been investigating robust algorithms for obtaining accurate motion estimation. Specifically, accuracy obtainable by using circular targets has been studied thoroughly. A mathematical model for the circular target is proposed and a careful error analysis has been made to study the effects of image quantization, camera calibration errors, image noise, and perspective distortion. An algorithm for locating the center of the circular target has been developed, which can achieve measurement accuracy that is an order of magnitude better than existing methods. This algorithm is to be used with motion estimation methods based on point correspondences.

Issues in measuring moving structures. We carried out an experiment involving a small structure (a simple frame). we subjected the structure to a non-zero initial displacement and zero initial velocity and recorded the structure's motion using a color video camera. We processed the image data to estimate the vertical and horizontal nodal displacements, then gave these displacement estimates to a parameter estimation program to estimate five constitutive structural parameters.

From this experiment, we discovered several important issues in structural parameter estimation using TV cameras. The experiment showed that image resolution, field interlace, and camera shutter speed are the key factors limiting the accuracy of our measurements. Based on the results of this experiment, we have a good idea of how to minimize the effects of image field interlace, how to increase the accuracy of rotation measurements, and how to deal with the high shutter speed of the camera. These methods will be explored in future research.

Stereo TV camera facility. In order to increase the accuracy of feature location and motion estimation, we plan to track the features of a moving structure by a pair of stereo TV cameras. After careful considerations, we have decided to put together ann system which will first record the two stereo video sequences on tapes (SVHS). The two tapes will

then be digitized to provide images for analysis. This facility involves a fair amount of video equipment. Fortunately, funds for equipment are available from a recent NSF grant received by the PI. Thus, we expect to have this facility operational in the near future.

PUBLICATIONS:

SHE, A.C., K.D. HJELMSTAD, and T.S. HUANG. Structural damage detection using stereo camera measurements. *Proceedings Nondestructive Evaluation of Civil Structures and Materials* (Boulder, CO, May 1992). ACTC Document No. 92-19-01.

SHE, A.C., K.D. HJELMSTAD, and T.S. HUANG. Nondestructive evaluation of civil structures and materials using stereo camera measurements. *Proceedings International Conference on Pattern Recognition* (The Hague, The Netherlands, August 1992) 708-711 (1992). ACTC Document No. 92-19-02.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

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T.S. Huang

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* Expected completion date

SMART STRUCTURES USING EMBEDDED OPTICAL FIBER STRAIN SENSORS
(Project No. 20)

by

S.L. Chuang, Associate Professor of Electrical and Computer Engineering

PROBLEM STUDIED:

Polarimetric Optical Fiber Strain Sensor. An optical polarimetric strain sensor using low and high birefringence fibers was investigated theoretically and demonstrated experimentally. The sensor measures internal strain in concrete structures.

Spectroscopic Fiber Optic Temperature Sensor. A fiber optic temperature sensor based on the spectral emission of neodymium doped optical fiber was built and studied experimentally. The spontaneous emission from small sections of optical fiber is measured and calibrated to the temperature of the fiber section.

SUMMARY OF MOST IMPORTANT RESULTS:

Polarimetric Optical Fiber Strain Sensor. A theoretical model and a laboratory experimental set-up were developed to study the sensor. Concrete cylinders were tested under uniform compression and the optical signal was correlated to resistance strain gauge readings. The theoretical model was used to optimize the orientation of the fiber relative to the strain field in order to maximize its resolution. Furthermore, the model helped us to understand the effect of strain on the transmission of light in the fiber; the model is also general enough to be expanded to any sensing length, beat length, wavelength, and different strain field configurations. Tests were carried out on many fibers of different characteristics to understand the effect of the jacket thickness and initial birefringence. Experiments using the Poincare sphere representation clearly characterizes the strain dependent behavior of the fibers by the state of polarization of the transmitted light. Theoretical and experimental results show good agreement.

The sensor was optimized using a high birefringence fiber, and applications of the sensor in more complex structural elements are being developed. The durability of the fibers inside concrete has been a concern to us from the beginning of the project, since long lasting sensors are desirable. Fifteen months old samples have been tested and show no deterioration of the fiber. Also, a miniaturized version of the system was proposed for actual implementations of the sensor.

Spectroscopic Fiber Optic Temperature Sensor. The viability of a temperature system based on the spontaneous emission of neodymium doped optical fiber was investigated. Current results confirm that with additional calibration and field testing, the temperature sensor may have broad application in smart civil and aeronautical structures.

PUBLICATIONS:

POPE, C., S.P. WU, S.L. CHUANG, J. CALERO, and J. MURTHA. An integrated fiber optic strain sensor. *Proceedings SPIE Conference on Optical Design and Processing Technologies and Applications 1779*, 113-121 (1992). ACTC Document No. 92-20-01.

CALERO, J., S. WU, C. POPE, S.L. CHUANG, and J.P. MURTHA. Theory and experiments on polarimetric strain sensors. *Journal of Lightwave Technology*, submitted.

WU, S., C. POPE, J. CALERO, S.L. CHUANG, and J.P. MURTHA. Comparison of high and low birefringence fibers as polarimetric strain sensors in concrete. *Photonics Technology Letters*, submitted.

WU, S. Polarimetric optical fiber strain sensors. M.S. thesis, S.L. Chuang, advisor (1993*).

POPE, C. Fiber optic strain and temperature sensors. M.S. thesis, S.L. Chuang, advisor (1993*).

CALERO, J. Concrete smart structures using embedded optical fiber strain sensors. Ph.D. thesis, J.P. Murtha, advisor (1994*).

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

S.L. Chuang

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Sou-Pan Wu	M.S., Elec. and Computer Eng., May 1993*

* Expected completion date

REDUCED STRUCTURAL DYNAMICS CALCULATIONS
(Project No. 21)

by

A.R. Robinson, Professor of Civil Engineering

PROBLEM STUDIED:

The problem tread is the reduction of the computational effort needed in numerical step-by-step dynamic structural analysis.

SUMMARY OF MOST IMPORTANT RESULTS:

Methods were devised to reduce computational effort in three important respects:

(1) When the input is very rapid, the use of integrated equations of motion and integrated variables, combined with an improved method for the integration of the differential equations, make it possible to use much larger time intervals than in the conventional approach;

(2) The calculations required for handling material nonlinearity were reduced greatly by using a new interpolation scheme in conjunction with the methods of (i); and

(3) A method was devised to remove the degrees of freedom that are responsible for the presence of very high frequencies from the dynamical equations of the system and to treat them algebraically in a perturbation method. Again, here the time integral can be much larger than in the standard analysis.

In a test problem for a two-story elasto-plastic frame, the new approach required only 10 percent of the computational effort that is needed by the methods generally used.

PUBLICATIONS:

CHEN, C.-C. and A.R. ROBINSON. Improved time-history analysis for structural dynamics. Engineering Mechanics, *Proceedings of the Ninth Mechanics Conference of ASCE*, (L.D. Lutes and J.M. Niedwicki, eds.) New York, 449-452 (1992). ACTC Document No. 92-21-01.

CHEN, C.-C. and A.R. ROBINSON. Improved time-history analysis for structural dynamics calculations I: Treatment of rapid variation of excitation and material nonlinearity. *Journal of Engineering Mechanics, ASCE*, accepted (no reference available).

ROBINSON, A.R. and C.-C. CHEN. Improved time-history analysis for structural dynamics calculations II: Reduction of the effective number of degrees of freedom. *Journal of Engineering Mechanics, ASCE*, accepted (no reference available).

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

A.R. Robinson

RESEARCH ASSISTANTS:

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* Expected completion date

NDE OF DAMAGE IN STRUCTURES USING FORCED DYNAMIC RESPONSE MONITORING
(Project No. 22)

by

K.D. Hjelmstad, Associate Professor of Civil Engineering
S.L. Wood, Associate Professor of Civil Engineering

PROBLEM STUDIED:

Many methods of nondestructive testing of structures sense local properties of materials. Such methods solve problems like finding embedded inclusions (e.g., reinforcing steel bars in concrete) quite effectively. Certain aspects of structural performance, however, cannot be assessed locally. The load path of a structure, for example, depends upon how the structural elements work together. An interruption or alteration in a load path may signal structural distress or impending failure. Global nondestructive testing methods are needed to aid such assessments.

Large-scale testing methods, such as forced vibration tests, have been around for some time, but have suffered from the absence of effective computational procedures to manage the vast amounts of data — essentially a problem in system identification and parameter estimation. One of the main forces driving research in system identification and parameter estimation today is the promise that these tools hold for establishing the theoretical underpinning of many important nondestructive testing methods. One day it might be possible to mount instruments on a structure, excite it, and determine exactly the location and extent of damage to the structural components. It might also become feasible to design and build structures with *in situ* monitoring devices, and use them to diagnose impending problems. The realization of such technologies depends upon the development of the analytical engine to drive them.

SUMMARY OF MOST IMPORTANT RESULTS:

The principal accomplishment of the present research program has been the development of a new family of parameter estimation algorithms for statically loaded, freely vibrating, or dynamically loaded structures. The methods are an advance beyond previous methods in that they are suitable for complex structural systems; they allow *a priori* evaluation of the minimum information required, and they deal with incomplete measurements in a rigorous, systematic manner. The methods have been implemented in a computer program which can serve as a research tool, as well as a diagnostic tool, for investigating the intrinsic identifiability of the member properties of a structure prior to physical implementation of an instrumentation scheme and can be used to optimize the location and sensitivity of the instruments. Three methods have been developed to deal with incomplete measurements in a noisy environment and have been implemented with a scheme for arbitrary parameter grouping. Parameter grouping is crucial to damage detection with extremely sparse measurements. The new algorithms have been thoroughly tested with simulations in an analytical environment.

The static parameter estimation problem has been re-examined in the context of *output error* methods (minimize $\|u - k^{-1}(x)f\|$), in contrast with the *equation error* methods (minimize $\|K(x)u - f\|$) developed previously.Both approaches have been augmented with the inequality constraint $x \geq 0$ and are solved using the method of Recursive Quadratic Programming. The addition of the constraint adds greatly to the stability of the methods when measurements are sparse, even when no constraints are binding at the final stage of the iteration. While computationally more intensive, the *output error* methods show a number of advantages of *equation error* methods, particularly when errors in measurement are large. Both approaches have been implemented and studied through Monte Carlo simulation.

Parameter estimation algorithms for modal and transient dynamic data have been formulated and implemented. The key to the development of the modal algorithm is to partition the governing system of equations in a particular way so that the form is similar to the static case. One can then simply apply the inequality constrained optimization methods already developed. The modal algorithm has been tested using real data from a building in California damaged in the Loma Prieta earthquake.

The key to the development of the transient dynamic algorithm is the way state estimation is done for measured versus unmeasured responses. In general, we assume that accelerations are measured at certain points. The velocity and displacement at those points are computed by direct quadrature of the acceleration field (an uncoupled signal processing operation). For the unmeasured degrees of freedom, the velocity and acceleration are expressed as finite differences of the displacement, making unmeasured displacements the primary state variable. This approach is possible because the unmeasured responses are noise free (by definition). Finally, the governing equations are put into a form similar to the static problem and parameter estimation is carried with the same tools as before. The transient dynamic problem introduces data management issues not present in the static and modal problems. For example, one must select the estimation time increment (for finite differences) and the size of the time window.

Our approach lends itself to the development of a general purpose program suitable for analyzing all forms of data for the target class of problems. This program is essentially complete and has been tested on a number of sample data sets.

PUBLICATIONS:

HJELMSTAD, K.D., S.L. WOOD, and S.J. CLARK. Parameter estimation in complex linear structures. SRS Report No. 557, UILU-ENG-90-2015. Department of Civil Engineering, University of Illinois, Urbana (1990).

CLARK, S.J. Member stiffness estimation in linear structures from static and vibrational response. M.S. Thesis, K.D. Hjelmstad and S.L. Wood, advisors (1989). ACTC Document No. 89-22-01.

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BANAN, M.R., M.R. BANAN, and K.D. HJELMSTAD. Parameter estimation in complex linear structures. *Proceedings of the Sixth Specialty Conference on Probabilistic Mechanics and Structural and Geotechnical Reliability*, 571-574 (1992). ACTC Document No. 92-22-03.

ALCOE, D.J. and K.D. HJELMSTAD. Identification of parametric finite element models using experimental modal data. Report No. SRS 566, UILU-ENG-92-2003. University of Illinois at Urbana-Champaign.

BANAN, M.R. Parameter estimation of finite element models based on static, modal, or forced transient response. Ph.D. thesis, in preparation.

BANAN, M.R., M.R. BANAN, and K.D. HJELMSTAD. Parameter estimation of finite element models based on static, model, or forced transient response. Technical Report in preparation.

BANAN, M.R., M.R. BANAN, and K.D. HJELMSTAD. Two parameter estimation methods for mathematical modeling of complex structures, part I: computational aspects of the static and modal problems. Paper in preparation.

BANAN, M.R., M.R. BANAN, and K.D. HJELMSTAD. Two parameter estimation methods for mathematical modeling of complex structures, part II: numerical simulation studies for static data. Paper in preparation.

BANAN, M.R., M.R. BANAN, and K.D. HJELMSTAD. Estimation of constitutive parameters from modal data: a case study. Paper in preparation.

BANAN, M.R., M.R. BANAN, and K.D. HJELMSTAD. Estimation of structural parameters from transient dynamic response in the time domain. Paper in preparation.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

K.D. Hjelmstad
S.L. Wood

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* Expected completion date

ELECTROMAGNETIC SENSING OF CONCRETE
(Project No. 23)

by

W.C. Chew, Professor of Electrical and Computer Engineering

PROBLEM STUDIED:

Electromagnetic properties of concrete.

SUMMARY OF MOST IMPORTANT RESULTS:

Generate a database for the electromagnetic properties of concrete at different curing times, sand/cement ratio, etc. Developed two measurement systems for measuring electromagnetic properties of concrete.

PUBLICATIONS:

CHEW, W.C. Waves and Fields in Inhomogeneous Media. Van Nostrand Reinhold, New York (1990).

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CHEW, W.C. and Y.M. WANG. A fast algorithm for solution of a scattering problem using a recursive aggregate tau matrix method. *Microwave Optical Tech. Letters, 3*:5, 164-169 (1990). ACTC Document No. 90-23-12.

WANG, Y.M. and W.C. CHEW. An efficient algorithm for solution of a scattering problem. *Microwave Optical Technology Letters, 3*:3, 102-106 (1990). ACTC Document No. 90-23-13.

WANG, Y.M. and W.C. Chew. Application of the fast recursive algorithm to a large inhomogeneous scatterer for TM polarization. *Microwave Optical Technology Letters, 4*:3, 155-157 (1991). ACTC Document No. 90-23-14.

OTTO, G.P., W.C. CHEW, and J.F. YOUNG. A large open-ended coaxial probe for dielectric measurements of cements and concretes. *Proceedings Nondestructive Evaluation of Civil Structures and Materials Conference* (Boulder, CO, October 1990). ACTC Document No. 90-23-15.

CHEW, W.C. Recursion relations for three-dimensional scalar addition theorem. *Electromagnetic Waves Applications, 6*:2, 133-142 (1992). ACTC Document No. 91-23-16

FRIEDRICH, J.A. Multiple scattering by spheres for effective permittivity calculations. M.S. thesis, W.C. Chew, advisor (1991). ACTC Document No. 91-23-17.

OTTO, G.P. Open-ended coaxial waveguides for measuring the dielectric properties of materials. M.S. thesis, W.C. Chew, advisor (1990). ACTC Document No. 91-23-18.

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PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

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W.C. Chew

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Gregory P. Otto	M.S., Electrical Engineering, January 1990

TITLE OF INVENTIONS (by name only):

(1) A broadband coaxial dielectric measurement cell for large samples.

(2) A broadband nondestructive contact type coaxial dielectric measurement probe for large samples.

ACCELERATED TESTS FOR SOIL PROPERTIES
(Project No. 24)

by

G. Mesri, Professor of Civil Engineering
W. Tang, Professor of Civil Engineering

PROBLEM STUDIED:

Subsurface exploration plays a significant role in nearly every type of construction. Ground condition is frequently the source of unexpected engineering problems, costs, disputes, and delays. This research study focused on the feasibility and reliability of using accelerated tests for assessing the site conditions particularly the soil properties at a given site.

SUMMARY OF MOST IMPORTANT RESULTS:

Undrained Shear Strength from Laboratory or In Situ Tests. Stability analysis of construction in soft clays and silts is carried out in terms of undrained shear strength. The quality of a shear test for obtaining undrained strength is measured by its simplicity, the reproducibility of its results and the fact that the values it yields have been calibrated against the observed behavior of a significant number of instabilities. The most comprehensive calibration in soft clays and silts has been carried out for the in situ vane shear test leading to a simple expression for mobilized strength in terms of the preconsolidation pressure. The existing total database on undrained shear strength from laboratory tests was analyzed to show that more time consuming and less economical laboratory tests only confirm the expression for mobilized undrained strength that previously resulted from the in situ vane test experience.

A Probabilistic Model for Evaluating Database. A method has been developed for analyzing the uncertainties involving the use of accelerated tests, such as index properties tests and simple in situ tests, and empirical relationship in design. For instance, the mobilized undrained strength at a site can be predicted using the in situ cone or the vane tests. Reliability of the geotechnical design will depend on the number of each type of tests measured, the expected size of the failure zone and the respective calibration uncertainty associated with the accelerated tests. Although prediction based on the vane tests is more accurate, same reliability level of geotechnical performance can sometimes be achieved by a larger number of cone tests or by increasing the design factor. Thus, our method provides essential information for planning cost-effective site characterization and exploration program.

Post Densification Modulus and Penetration Resistance. Cone penetration test is frequently used for control of ground densification before construction, by blasting, vibrocompaction, or dynamic compaction. Freshly densified clean sands exhibit a substantial increase in stiffness and cone penetration resistance with time under drained aging conditions. Assuming that aging of clean sands is a frictional phenomenon, and that cone penetration resistance is determined by stiffness of sand and effective horizontal stress,

equations have been developed for predicting the increase in cone resistance with time. The proposed equations were tested using laboratory blast densification data, and were calibrated using in situ post blast and vibrocompaction cone data in a deep sand deposit. In the absence of cone penetration tests with time or for planning of such in situ measurements, the proposed equation can be used to extrapolate measurements that are carried out immediately after ground modification.

Cone Factor for Soft Clays and Silts. Undrained shear strength is determined from the end resistance of push cone penetration test using the bearing capacity equation for undrained deep penetration. This procedure includes an unknown cone factor which needs to be determined at every site. Using extensive database on undrained shear strength from the triaxial compression mode of shear, strain rate effect on undrained shear strength, and undrained shear strength mobilized in embankment, footing and excavation failures, a $N_k(mob) = 16$ has been determined, for a wide range of soft clays and silts. This value of cone factor, together with cone penetration resistance, leads to mobilized strength, which is directly used for embankment, foundation and excavation stability analyses.

Cone Factors for Stiff Fissured Clays. The most useful data on N_k values of stiff fissured clays are in terms of $N_k(UU)$ from 100mm diameter specimens. A correlation between $N_k(UU, 100mm)$ and plasticity index has been developed in terms of fissure spacing normalized to cone diameter. In order to appreciate the source of the difference between $N_c = 9$ and $N_k(UU), 100mm)$ values in the range of 11 to 30, the role of fissures and strain rate must be considered. The structural creep effect introduces a factor of 1.2 into the bearing capacity equation when $s_u(cone)$ is replaced by $s_u(UU)$. The major portion of the remaining difference between $N_k(UU, 100mm)$ and $1.2\ N_c = 11$ is related to the fissured nature of stiff clays and to local softening during undrained shear. The fissures contribute to the difference between $s_u(cone)$ and $s_u(UU, 100mm)$ as a result of the difference between strength along fissures and through intact materials, and of a strain rate effect associated with local softening. Both effects should increase with the plasticity of the clay. Therefore, the value of $N_k(UU, 100mm)$ depends on fissure spacing and plasticity index.

For fissure spacing larger than about the diameter of the cone, the cone bearing capacity substantially reflects the intact strength of the clay. The difference between $s_u(cone)$ and $s_u(UU, 100mm)$ and, therefore, the magnitude of $N_k(UU, 100mm)$ reaches a maximum at a fissure spacing of about 2 to 4 times the diameter of the cone. The fissure and local softening effects are most significant for high plasticity marine clays for which the difference between fissure strength and intact strength is large. Fissures have less influence on the $N_k(UU, 100mm)$ of glacial clays of low plasticity. However, glacial clays are also more likely to be free from fissures and other discontinuities. For fissure spacings less than about 1/6 the diameter of the cone, slip occurs mainly along the discontinuities and the cone bearing capacity reflects the effect of the fissures. In this case the difference between $1.2\ N_c(UU, 100mm)$ is related to local softening and to the sample disturbance effect on $s_u(UU)$.

Cohesion Intercept in Effective Stress Stability Analysis. The cohesion intercept in the Coulomb shear strength equation has a significant influence on the location of the slip surface and the factor of safety. The cohesion intercept results from a linear approximation of a segment of a non-linear shear strength against effective normal stress relationship. Shear strength on a slip surface, at the instant of a global instability, may range from residual strength to peak strength for stiff clays, and from large strain strength to peak strength for soft clays. Peak strength controls local development of slip surface, but it may

not be available during global failure. The critical slip surface for an initial slide is determined using the peak shear strength. However, a mobilized strength equal to or less than the peak strength is used to define the factor of safety. Effective stress stability analysis of slope failures has resulted in a reduction factor to the peak strength in order to obtain the mobilized strength for first time slides. For over sixty slope failures in soft and stiff clays, the values of c'(mob) are in the range to 0 to 26 kPa as compared to 1 to 150 kPa for c' of the clays involved in the failures.

Reliability Analysis Considering Geologic Anomaly. The presence of anomalous soil materials, that is materials other than those described in the design profile, is often a major cause of geotechnical failures. Non-encounter by borings and cone penetrometers across the site could minimize the likelihood of anomaly presence and, if present, in limiting the anomaly to tolerable size. Probabilistic procedures have been developed to incorporate engineers' experience and judgment on the local geology and to relate exploration effort (e.g., number and configuration of borings) to the probability of presence of such anomaly, its size and location. Efficient methods are also developed for evaluating the probability of geotechnical failures considering possible presence of geological anomalies. By identifying critical locations where the presence of anomalous materials will be most hazardous, results of our study will further facilitate the planning of cost-effective site exploration program for mitigating anomaly-induced geotechnical failures.

Swelling Pressure of Clay Shales. A concept of unsaturated fissured shale is introduced and is used to explain the magnitude and time-rate of swelling pressures measured in laboratory tests and mobilized in the field. The magnitude of swelling pressure mobilized by an excavation-exposed shale surface against a fixed rigid support is expressed in terms of constant water content expansion of the shale mass adjacent to the excavation. An analytical formulation is developed for predicting time-rate of swelling pressure development on a rigid lining in a circular tunnel. Both the concept of mobilized swelling pressure as well as the time dependent development of swelling pressure, are examine by means of predictions of swelling pressure for a tunnel in Taylor shale.

PUBLICATIONS:

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HALIM, I.S. and W.H. TANG. Bayesian method for characterization of geological anomalies. *Proceedings IEEE First International Symposium on Uncertainty Modeling and Analysis*, Maryland, December 1990, pp. 585-594 (1990). ACTC Document No. 91-24-04.

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TANG, W.H. Recent developments in geotechnical reliability. Keynote lecture at the Conference on Probabilistic Methods in Geotechnical Engineering, Canberra, Australia, February 1993.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

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NDE OF MASONRY BUILDINGS
(Project No. 26)

by

D.P. Abrams, Professor of Civil Engineering

PROBLEM STUDIED:

Various methods of nondestructive evaluation for unreinforced masonry building structures were explored. NDE techniques included (a) ultrasonic and sonic wave velocity tests for assessing condition of masonry walls, (b) flat jack tests for estimating insitu vertical compressive stress and elastic modulus, and (c) in-place shear tests for estimating lateral strength of masonry shear walls. The applicability of video imaging techniques was also studied for measurement of in-plane wall deformations. The relation between NDE estimates and overall wall behavior was studied through a series of full-scale tests of actual masonry walls, and a companion analytical study.

SUMMARY OF MOST IMPORTANT RESULTS:

The study demonstrated the precision of NDE techniques when applied to masonry building structures. Wave velocity tests proved to be an appropriate technique for assessing the interior condition between leaves of masonry. Using data from such tests, maps representing the relative homogeniety of a wall could be constructed. Sonic tests revealed less data scatter than ultrasonic tests because wavelengths were longer and more consistent with brick dimensions.

The flat-jack technique proved to be accurate within 5% for estimating vertical compressive stress, and within 10% for estimating elastic modulus at low values of vertical stress.

Full-scale tests of actual masonry walls revealed that they had considerable strength and ductility after formation of the first crack. This finding was significant for the development of procedures for estimating lateral strength of an overall building system in terms of the strengths of its individual components.

NDE estimates of masonry shear strength were found to exceed actual shear strengths by 40% to 70%. The discrepancy was attributed to the common practice of integrating shear stress at a point across the full gross area of a masonry wall. Excellent agreement between NDE estimates and actual strengths were observed if nonlinear effects related to flexural cracking, and the redistribution of shear stress, are considered, A failure theory for lateral shear strength of unreinforced masonry walls was developed to understand these nonlinear effects. A computer program was written to determine ultimate lateral strength of cracked walls with various combinations of vertical stress, length-to-height aspect ratios, and masonry shear, tensile and compressive strengths. A simple evaluation methodology was proposed using a set of strength tables that were generated using the computer program.

The research proved to be timely because codes for evaluation of unreinforced masonry construction are just now evolving. Since the 1989 Loma Prieta Earthquake in

Northern California, a large inventory of masonry buildings had to be evaluated prompting the need for a new Appendix to the Uniform Code for Building Conservation. The American Society for Testing and Materials is proposing new standards for flat-jack tests and the in-place shear test. The Applied Technology Council is commencing development of recommendations for rehabilitation of masonry buildings. The National Earthquake Engineering Research Center has initiated a new program on evaluation of existing unreinforced masonry buildings. The principal investigator has been active in these developments, and is the chairman of the last two activities.

PUBLICATIONS:

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EPPERSON, G.P. and D.P. ABRAMS. Nondestructive evaluation of masonry buildings, 1989. ACTC Document No. 89-26-03.

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ABRAMS, D.P. and N. SHAH. Design, construction and utilization of a post tensioned masonry laboratory reaction structure. *Proceedings of Sixth Canadian Masonry Symposium* (University of Saskatchewan, June 1992) 213-221. ACTC Document No. 92-26-06.

ABRAMS, D.P. Safe limits for lateral capacity of cracked URM walls. *Proceedings of Sixth Canadian Masonry Symposium* (University of Saskatchewan, June 1992) 235-246. ACTC Document No. 92-26-07.

ABRAMS, D.P. Strength and behavior of unreinforced masonry elements. *Proceedings of Tenth World Conference on Earthquake Engineering* (Madrid, Balkema Publishers, Rotterdam, July 1992) 3475-3480. ACTC Document No. 92-26-08.

ABRAMS, D.P. Masonry as a structural material. *Proceedings of ASCE Materials Engineering Conference*, Atlanta, GA, August 1992. Also reprinted as "Masonry Carries the Load," ASCE *Civil Engineering, 63*:2, February 1993. ACTC Document No. 92-26-09.

ABRAMS, D.P. and N. SHAH. Cyclic load testing of unreinforced masonry walls. Technical Report, December 1992. ACTC Document No. 92-26-10.

XU, W. and D.P. ABRAMS. Evaluation of lateral strength and deflection for cracked unreinforced masonry walls. Technical Report, December 1992. ACTC Report No. 92-26-11.

ABRAMS, D.P. Diagnosing lateral strength of existing concrete or masonry buildings. *Proceedings of ASCE Structures Congress* (Irvine, CA, April 1993).

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

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AN ENGINEERING APPROACH TO NDE OF MATERIAL PROPERTIES
(Project #27)

by

D.L. Marriott, Professor of Mechanical Engineering
R.L. Weaver, Professor of Theoretical and Applied Mechanics

PROBLEM STUDIED:

The overall objective was the identification of correlations between parameters relating toughness and those which can be measured conveniently and nondestructively using conventional UT equipment and modest peripherals which can be transported to the construction site. This objective was based on the knowledge that, although complete relationships have not been formulated, there are physically reasonable correlations between microstructure and toughness parameters such as transition temperature shift, and known correlations between microstructure and UT parameters such as attenuation and backscatter. It is also based on the knowledge that, while conventional UT microstructural assessment procedures are exceedingly difficult and not amenable to field implementation, recently envisioned new methods promise to be more robust.

SUMMARY OF MOST IMPORTANT RESULTS:

Strong correlations were demonstrated between ultrasonic tests (coherent attenuation and multiple diffuse side scatter) and mechanical properties such as Charpy toughness of AISI and other steels under a variety of heat treatments. The correlations was consistent with the hypothesized grain sized dependence for both ultrasonic and mechanical behavior. The multiple diffuse side scatter ultrasonic technique has been shown to be more feasible than had heretofore been imagined, to require less spatial averaging and to be applicable to a wider variety of specimen geometries.

A new and economical fracture toughness test in a round notched bar was developed and compared to the ASTM compact tension method.

PUBLICATIONS:

WALCZAK, M.J. Development of the circumferential notch fracture test for steels with controlled heat treatment procedures. M.S. thesis, R.L. Weaver, advisor (1989). ACTC Document No. 89-27-01.

WEAVER, R.L. Ultrasonic diffuse field measurements of grain size. *Nondestructive Testing and Evaluation in Manufacturing and Construction* (Henrique L. M. dos Reis, ed., Hemisphere) 425-434 (1990). ACTC Document No. 91-27-02.

WEAVER, R.L., W. SACHSE, K. GREEN, and Y. ZHANG. Diffuse ultrasound in polycrystalline solids. *Proceedings of Ultrasonics International*, 507-510 Butterworth-Heinemann (1992).

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NDE SYSTEMS
(Project No. 30)

by

W.C. Chew, Professor of Electrical and Computer Engineering
H. Lee, Professor of Electrical and Computer Engineering
J.P. Murtha, Professor of Structural and Hydraulic Engineering

PROBLEM STUDIED:

The objective of this research program is to develop microwave subsurface imaging techniques for NDE of civil structures and materials. Research tasks include

(1) mathematical analysis and physical modeling of the system,
(2) imaging algorithm design, development, and simulation,
(3) implementation of data acquisition system,
(4) laboratory experiments,
(5) system performance evaluation and resolution analysis, and
(6) field experiment.

SUMMARY OF MOST IMPORTANT RESULTS:

Image reconstruction in two-dimensional and three-dimensional with impulse radar data, numerical simulation codes developed for two-dimensional and three-dimensional, and inverse scattering algorithms were derived.

All proposed research tasks have been successfully accomplished during the program period. Research results have been fully documented in the form of publications, computer records, and video tapes. Here we briefly describe the results of each task.

During the early stage of this research program, we have performed detailed mathematical analysis and physical modeling of the imaging system, based ont he pulse-echo model. Subsequently, high-resolution imaging algorithms have been designed and implemented based on the backward wave propagation technique. In terms of algorithm structure, this imaging technique is a pulse-echo multiple-frequency tomographic method.

To perform laboratory experiments for performance evaluation, test specimens were constructed with various configurations of rebar and void structures. By scanning the SIR transducer, synthetic-aperture data acquisition has been conducted. Image formation process has then been applied to the laboratory data. Resultant images have successfully demonstrated the capability of the proposed imaging technique. The imaging experiments include both 2D cross-sectional imaging and 3D volume imaging cases.

The purpose of the field experiment was to apply this technique to evaluate the structural configuration and integrity of portions of the New York State Capitol building in Albany, NY. The radar was used to determine and verify structural members and configuration of the building. The technique involved scanning surface areas of the building (usually floors and walls) with a SIR system and with the collected data for subsequent image reconstruction. The evaluation consisted of an initial calibration of the radar on

construction typical of that found in the building to estimate the propagation velocities. Using the estimated velocities, holographic imaging techniques provided for visualization of the structural members and configurations. The radar evaluation was successful for the following features: the depth, span, and size of beams and girders in floors and columns in walls; the thickness of floors and walls; the amount of spring in masonry arches; the depth, span and size of the beams supporting the arches; the mechanical stepping and thickness of the outer granite facing; the presence and location of anchors between granite blocks; and the presence of wire mech and reinforcement in concrete.

PUBLICATIONS:

LEE, H., J. SILKAITIS, and D.P. SULLIVAN. Optimal algorithm for high resolution time delay estimation. *Acoustical Imaging, 17* (H. Shimizu, N. Chubachi, and J. Kushibiki, eds.) Plenum Press, New York, 265-272 (1989).

YANNAKAKIS, E.J. Computer modeling of impulse radar using the finite difference method. M.S. thesis, W.C. Chew, advisor (1989). ACTC Document No. 89-30-01.

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CHEW, W.C. A derivation of the vector addition theorem. *Microwave Optical Technical Letters, 3*:7, 256-260 (1990).

MOGHADDAM, M., E.J. YANNAKAKIS, and W.C. CHEW. Modeling of the subsurface interface radar. *Journal of Electromagnetic Waves and Applications, 5*:1, 17-39 (1991). ACTC Document No. 90-30-06.

WANG, Y.M. and W.C. CHEW. Limited angle inverse scattering problems and their applications for geophysical explorations. *International Journal on Imaging Systems and Technology, 2*:2, 96-111 (1990). ACTC Document No. 90-30-07.

LIN, Z-C., H. LEE, and T.S. HUANG. Estimating rigid-body motion from three-dimensional data without matching point correspondences. *Journal of Imaging Systems and Technology, 2*, 55-62 (1990). ACTC Document No. 90-30-08.

MAST, J.E., H. LEE, W.C. CHEW, and J.P. MURTHA. Pulse-echo holographic techniques for microwave subsurface NDE. *Proceedings Nondestructive Evaluation of Civil Structures and Materials Conference* (Boulder, CO, October 1990) 177-191 (1990). ACTC Document No. 90-30-09.

MOGHADDAM, M. and W.C. CHEW. Nonlinear two-dimensional velocity profile inversion in the time domain. *IEEE Geoscience and Remote Sensing, GE-30*:1, 147-156 (1992). ACTC Document No. 91-30-10.

GOLDGOF, D.B., T.S. HUANG, and H. LEE. Terrain analysis from curvature profiles. *International Journal of Imaging System Technology, 2*:3, 169-182 (1990). ACTC Document No. 90-30-11.

WANG, Y.M. and W.C. CHEW. Accelerating the iterative inverse scattering algorithms by using the fast recursive operator algorithm. *Radio Science, 27*:2, 109-116 (1992). ACTC Document No. 91-30-12.

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PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

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FELLOWS:

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Mahta Moghaddam	Ph.D., Electrical Engineering, September 1991
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Terry W. Wall, Jr.	M.S., Civil Engineering, January 1993
William Weedon	Ph.D., Electrical and Computer Eng., May 1994*
Alan Yang	M.S., Electrical and Computer Eng., January 1990
Elias J. Yannakakis	M.S., Electrical Engineering, June 1989

* Expected completion date

ON-LINE DISPLACEMENT MONITOR TO MEASURE RESIDUAL STRESS
(Project No. 34)

by

D.F. Socie, Professor of Mechancial Engineering
J. Mazumder, Professor of Mechnical Engineering

PROBLEM STUDIED:

Three dimensional transient finite element model for solidification and residual stress in the GMAW process for AISI 304 Stainless Steel.

SUMMARY OF MOST IMPORTANT RESULTS:

The severe and non-uniform heating and cooling in and around the weld region changes the microstructure of the material by recrystallization, grain growth and phase transformation. These microstructures determine the thermal and mechanical properties of the weldment. Transient thermal cycles cause thermal expansion, plastic deformation and consequently, residual stress and distortions in the weld joint. The objective of the research is basically to develop the three dimensional transient mathematical model to predict solidification microstructure parameters such as primary dendrite arm spacing and tip radius, as well as to predict the residual stress embedded in the workpiece during GMAW. Initially, the challenge was to develop a method to simulate the metal transfer mechanism in MIG welding. A dynamic mesh generation scheme was generated to realistically simulate the MIG process and then subsequently model the heat and stress distribution. Once this fundamental step was completed by P. Tekriwal (Ph.D., 1989), J. Choi started working on predicting the microstructure to complete the simulation of the whole process.

Solidification analysis was simulated using the formulation based on Hunt-Trivedi model. Initially, history of temperature, solidification speed and primary dendrite arm spacing were predicted at the given node of interest which is a point on the top surface. Preliminary results show that the variation during the solidification time is usually in an order of magnitude. The temperature gradient was generally in range of 10^4 - 10^5° K/m, while solidification speed was appeared to slow down from 10^{-1} - 10^{-2} m/sec. About the dendrite arm spacing, the values were in range of 10^1 -10^2 μm. The range of the sizes was in good agreement with the values in the literatures. Stress analysis was done to simulate stress and strain history resulted from thermal load history. For the stress calculation, same mesh generation used ion the heat transfer analysis reported in the last meeting is applied in order to make the simulation consistent, and it is carried out separately. The analysis consists of a transient heat analysis followed by a thermal stress analysis. From the simulation, it can be predicted whether the magnitude of distortion is within the tolerance allowed, because the welding problems usually come from the over-distorted area due to improper welding process parameters. Preliminary data indicate that residual stress values increase with time. This research has been focused on describing the correlation between process parameter and microstructures as well as residual stress. A holographic interferometric technique was developed to measure the stress/strain. W. Norvell completed her

M.S. thesis demonstrating this technique using a soldering iron on the heat source. Presently, J. Choi is working with the U.S. Army Construction Engineering Research Laboratory (USA/CERL) to measure the temperature distribution and strain distribution during GMAW welding to validate the model.

PUBLICATIONS:

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TEKRIWAL, P.K. and J. MAZUMDER. Transient and residual thermal strain-stress analysis of arc welding processes. *Proceedings AIME 5th Engineering Foundation Conference on Modeling of Casting and Welding Processes* (Davos, Switzerland, September 1990) *113*:3, 211-218; *Journal of Engineering Materials and Techniques,* 336-343 (1990). ACTC Document No. 91-34-04.

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JONES II, D.J. Computer aided analysis of optical interference patterns resulting from mechanical deformations. M.S. thesis, D.F. Socie, advisor (1987). ACTC Document No. 91-34-06.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

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THRUST AREA

CONSTRUCTION SITE METROLOGY

VISUAL ACQUISITION OF THREE-DIMENSIONAL STRUCTURAL DATA FOR CONSTRUCTION
(Project No. 40)

by

N. Ahuja, Professor of Electrical and Computer Engineering

PROBLEM STUDIED:

The objective of this project was to solve the problem of surface reconstruction from actively acquired stereo images of large scenes having large depth ranges where it is necessary to aim cameras in different directions and to fixate at different objects.

SUMMARY OF MOST IMPORTANT RESULTS:

(1) We have developed an approach to the selection of new fixation points from the central visual field which is in near sharp focus.
(2) We have developed a methodology for selecting new objects for fixation in the peripheral field, for the integration of coarse-to-fine image acquisition, and coarse-to-fine surface reconstruction during refixation.
(3) We have developed an approach to optimally combine the stereo and focus based estimates when refixation on a new object has been achieved.
(4) We have developed a formulation for integrating camera calibration with dynamic surface reconstruction.
(5) We have evaluated the performance of stereo, focus, and vergence as reliable sources of three-dimensional depth information by considering the random errors in imaging parameters and the systematic errors in miscalibrating the imaging systems.

Together, the above results yield an approach/system for surface reconstruction for relatively general scenes. We have begun extension of the above active stereo paradigm to dynamic scenes containing moving objects. This involves control of the gaze direction, camera focus, and camera vergence to track moving objects and the use of the image sequences obtained during the camera reconfiguration for depth map construction.

PUBLICATIONS:

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DAS, S. Dynamic integration of camera motion, multiresolution image acquisition and coarse-to-fine surface reconstruction from stereo. Ph.D. thesis, N. Ahuja, advisor (1991).

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DAS, S. and N. AHUJA. Multiresolution image acquisition and surface reconstruction, *Proceedings Third International Conference on Computer Vision* (Osaka, Japan, December 1990) 485-488. ACTC Document No. 91-40-04.

ABBOTT, A.L. and N. AHUJA. Active surface reconstruction by integrating focus, vergence, stereo, and camera calibration. *Proceedings Third International Conference on Computer Vision* (Osaka, Japan, December 1990) 489-492. ACTC Document No. 91-40-05.

AHUJA, N. and A.L. ABBOTT. Active surface reconstruction: Integrating stereo, vergence, focus, aperture, and calibration. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, to appear. ACTC Document No. 92-40-06.

HWANG, Y.K and N. AHUJA. Gross motion planning — a survey. *ACM Computing Surveys, 24*:3, 219-292 (1992). ACTC Document No. 92-40-07.

SUBHODEV, D and N. AHUJA. Performance analysis of stereo, vergence, and focus as depth cues for active vision. *IEEE Transactions Pattern Analysis and Machine Intelligence*, submitted. ACTC Document No. 92-40-08.

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PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

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TITLE OF INVENTIONS:

"Active, Non-Uniform Imaging Camera," UIUC No. 92007

IMAGING AND VISION SYSTEMS FOR AUTOMATED CONSTRUCTION
(Project No. 43)

by

H. Lee, Professor of Electrical and Computer Engineering

PROBLEM STUDIED:

The objective of this research program is to develop imaging and vision systems to perform tracking, guidance, path planning, monitoring, and visualization for automated construction process. In addition, these systems can be applied to aid the functions of verification, documentation, and quantitative measurement of field operations.

SUMMARY OF MOST IMPORTANT RESULTS:

During the early stage of the research program, the effort has been concentrated on the development and implementation of the vision system with stereo cameras. With this vision system, laboratory experiments became feasible. Subsequently, research effort was devoted to the development of displacement and motion estimation algorithms. The main purpose is to realize the capability of high-accuracy 3D tracking of rigid objects.

The development of motion estimation algorithms has two major components. The first type is with feature selection and matching-correspondence information. The features considered are point and line features mainly because of the availability of these features in conventional construction materials and objects. Subsequently, we extended this work to include curvature features due to the property of rotation invariance. These techniques have been applied to field-experiment data and we have successfully demonstrated the feasibility and capability.

To simplify the computation complexity, high-speed algorithms have also been developed. These algorithms are realized based on the higher-order statistics of the image sequence. As a result, feature selection and matching correspondences are not required for this new motion estimation process. This enables us to implement motion estimation in real time.

Subsequent to the successful development of motion estimation algorithms for rigid objects, these techniques have also been elevated to a significant higher level for non-rigid objects. This is achieved by relaxing the key constraints in rigid-object motions. This allows us to perform motion estimation, tracking, and quantitative monitoring of expansion, flow, deformation, and multiple-object movement.

All proposed research tasks have been successfully accomplished during the program period. Research results have been fully documented in the forms of publications and computer records.

PUBLICATIONS:

LIN, Z-C., H. LEE, and T.S. HUANG. Estimating rigid-body motion from three-dimensional data without matching point correspondences. *International Journal on Imaging Systems and Technology, 2*:1, 55-62 (1990).

GOLDGOF, D.B., T.S. HUANG, and H. LEE. Feature extraction and terrain matching. *Proceedings IEEE Conference on Computer Vision and Pattern Recognition*, 899-904, (1988).

LEE, H., R. CHIAO, and D.P. SULLIVAN. Partial discrete vector space model for high-resolution beamforming. *Acoustical Imaging, 16* (L. W. Kessler, ed., Plenum Press) 601-611 (1988).

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GOLDGOF, D.B., T.S. HUANG, and H. LEE. Curvature based approach to terrain recognition. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 11*:11, 1213-1217 (1989). ACTC Document No. 89-43-04.

MAST, J.E. Subsurface holographic imaging with ground penetrating radar. M.S. thesis, H. Lee, advisor (1989). ACTC Document No. 89-43-05.

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GOLDGOF, D.B., T.S. HUANG, and H. LEE. Using gaussian and mean curvatures for terrain characterization. *Proceedings ANS Third Topical Meeting on Robotics and Remote Systems, 4-5* (Charleston, SC, March 1989) 1-8 (1989). ACTC Document No. 89-43-07.

GOLDGOF, D.B., T.S. HUANG, and H. LEE. Motion estimation from orthographic projections without correspondences. *Proceedings IEEE Computer Society Workshop on Visual Motion,* (Irvine, CA, March 1989) 352-358 (1989). ACTC Document No. 89-43-08.

GOLDGOF, D.B. Motion estimation from three-dimensional data. Ph.D. thesis, H. Lee, advisor (1989). ACTC Document No. 89-43-09.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

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RESEARCH ASSISTANTS:

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3D VISION FOR ENGINEERING CONSTRUCTION
(Project No. 45)

by

K.W. Wong, Professor of Civil Engineering

PROBLEM STUDIED:

To develop methodology to fully exploit the accuracy potential of computer vision systems for performing three-dimensional geometric measurements in a fully automated and real-time mode.

SUMMARY OF MOST IMPORTANT RESULTS:

Geometric distortion characteristics of vision systems. Experiments were conducted to study the pattern of geometric distortions and the stability of these distortion characteristics over time. Both the vision cameras and the frame grabber boards were found to have large geometric distortions during system warm-up. During the initial minutes after a system is powered up, geometric distortions could amount to as much as 30 pixels along the direction of scan, and about 0.06 pixels in the direction perpendicular to the scan lines. Even after more than 24 hours of continuous operation, there remained a cyclic drift along the scan direction with a peak-to-peak difference amounting to about 0.2 pixel.

However, within each frame, the geometric distortions were found to be highly systematic. A mathematical model was developed to model these distortions with resulting residual distortions consistently less than ± 0.05 pixels (standard deviation) within an image.

Method for automatic calibration of vision systems. A method was developed for the automatic calibration of vision systems using a three-dimensional target field. The calibration field consisted of 54 round, black targets on white background. There were 10 targets of 38-mm diameter, 8 targets of 76-mm diameter, and 36 targets of 102-mm diameter. Below each target is a six-digit binary bar code to represent its identification number. The three-dimensional coordinates of each target were determined by triangulation. Software was developed to automatically identify and locate the center of each target within an image, and then determine the position, orientation, as well as distortion characteristics of the camera.

Geometric calibration of zoom lenses. Because of the small focal planes of CCD sensors, zoom lenses were expected to play an important role in any future application of computer vision systems for site metrology. Laboratory studies of zoom lenses, having a focal range of 12.5-75 mm, showed that geometric distortions could amount to several tens of pixels across the focal plane, and that there were significant changes in the distortion patterns at different focal settings. Changes in position of the principal point amounting to as much as 90 pixels were measured. These changes were found to be highly systematic, repeatable, and stable over time. A mathematical model was developed to model the changes in the interior geometry of zoom lenses, with the resulting residual distortions amounting to less than ± 0.4 pixel (standard deviation) within the entire range of zoom.

Image correlation for 3-D information. A novel algorithm based on the principle of least-cost optimization was developed to generate 3-D information from stereo images. The algorithm was implemented with learning algorithms to achieve successful matches even in scenes of low contrasts such as surfaces of asphalt pavement. The algorithm was tested with images acquired by a stereo vision system. It automatically identify matchable points within a scene, and generate 3-D information for the entire scene. A scene consisting of 600 data points could be generated with a 286-class PC in less than 10 minutes of time. The algorithm has a matching accuracy of ± 1 pixel.

Image alignment by line triples. An algorithm was developed to automatically align two digital images by finding line triples and matching them in a stereo pair of images. Each line triple consisted of three line segments. The center segment could be either a straight line or a circular arc, while the two end segments must be straight. A line triple was characterized by the type of center segment, the length of the individual segments, and the magnitude of the two deflection angles.

Video documentation of engineering construction. Test results showed that accurate geometric measurements could be performed using commonly available camcorders. Accuracy of dimensional measurements ranging from 1/40 to 1/500 of the actual dimensions were obtained for objects located at distances of 2.6 m to 12 m from the cameras. Knowledge-based algorithms were developed for performing photogrammetric computation. Test results demonstrated the potential use of camcorders for video documentation of engineering construction. Such measurement techniques will also be useful for performing real-time geometric measurement in hazardous and/or inaccessible sites such as nuclear reactors, underground cavities, and small tunnels.

PUBLICATIONS:

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WONG, K.W., A.G. WILEY, and M. LEW. GPS-guided vision systems for real-time surveying. *Journal of Surveying Engineering, ASCE 115*:2, 243-252 (1989).

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WILEY, A.G. and K.W. WONG. Metric aspects of zoom vision. *SPIE Proceedings, 1395,* (Zurich, Switzerland, September 1990) 112-118 (1990). ACTC Document No. 90-45-03.

WONG, K.W., M. LEW, and Y. KE. Experience with two vision systems. *SPIE Proceedings, 1395,* (Zurich, Switzerland, September 1990) 3-7 (1990). ACTC Document No. 90-45-04.

LEW, M.S. Hierarchical techniques in stereo matching. M.S. thesis, T.S. Huang, advisor (1990). ACTC Document No. 91-45-05.

MASON, S.O. and K.W. WONG. Image alignment by line triples. *Photogrammetric Engineering and Remote Sensing 58*:9, 1329-1334 (1992). ACTC Document No. 91-45-06.

WONG, K.W., Y. KE, M. LEW, and M.T. OBAIDAT. Three-dimensional gaging with stereo computer vision. *International Congress on Industrial Vision Metrology, SPIE Proceedings, 1526,* (Winnipeg, Canada, July 1991) 17-26 (1991). ACTC Document No. 91-45-07.

WILEY, A.G. Metric aspects of zoom vision. Ph.D. thesis, K.W. Wong, advisor (1991). ACTC Document No. 91-45-08.

WONG, K.W., Y. KE, M. SLAUGHTER, and R. GRETEBECK. A computer vision system for mapping human bodies. *XVII Congress of the International Society for Photogrammetry and Remote Sensing, 29*:B5 (Washington, D.C., August 1992) 850-855 (1992). ACTC Document No. 92-45-09.

WILEY, A.G. and K.W. WONG. Geometric calibration of zoom lenses for computer vision metrology. *XVII Congress of the International Society for Photogrammetry and Remote Sensing, 29*:B5 (Washington, D.C., August 1992) 587-593 (1992). ACTC Document No. 92-45-10.

WONG, K.W. and M.T. OBAIDAT. DRSTEREO - A stereo measurement system for the PC. *1992 ASPRS/ACSM/RT Convention* (Washington, D.C., August 1992) 228-234 (1992). ACTC Document No. 92-45-11.

LEW, M.S., K.W. WONG, and T.S. HUANG. Multiscale stereo matching. *Proceedings Eleventh International Conference on Pattern Recognition* (The Hague, The Netherlands, August 1992) in press (1992). ACTC Document No. 92-45-12.

A.G. WILEY and K.W. WONG. Geometric calibration of zoom lenses for computer vision metrology. *Photogrammetric Engineering and Remote Sensing*, submitted January 1993. ACTC Document No. 93-45-13

LEW, M.S. Learning and feature selection in stereo matching. Ph.D. thesis, T.S. Huang, advisor (1993*).

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

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Sotiria Koloutsou	
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* Expected completion date

THRUST AREA

NEW MATERIALS AND TECHNOLOGIES FOR BUILDING CONSTRUCTION

CORROSION RESISTANT OXIDE COATINGS FROM METALLOORGANIC PRECURSORS
(Thesis Scale)

by

R.C. Buchanan, Professor of Ceramic Engineering

PROBLEM STUDIED:

Methods relating to the fabrication of High T_c superconducting thin films on silicon wafers are the subject of considerable research. The interest in developing High T_c films on silicon derives from the potential advantages to be gained from using superconductors as electrical current carrying vias, as Josephson junctions, and as superconducting quantum interference devices (SQUIDS).

SUMMARY OF MOST IMPORTANT RESULTS:

The processing and phase stability of $Ba_2YCu_3O_{7-x}$ High T_c thin films are seen to be critical aspects of the successful fabrication of this material. Metal neodecanoates of barium, yttrium, and copper were synthesized and mixed into a homogeneous, precipitate-free solution, which was spin-cast onto ZrO_2 coated silicon wafers. A minimum heat treatment temperature of 725° C in N_2 was needed to decompose the $BaCO_3$ present in the films. A phase map of the stability of $Ba_2YCu_3O_{7-x}$ as a function of heat treatment temperature and ambient showed both the upper and lower temperature boundaries to increase with decreasing P_{O2}, with the higher temperature boundary truncated at temperatures > 800° C from reaction of the films with the substrate. The high temperature decomposition mechanism for the high P_{O2} condition was seen to be nucleation of $BaCuO_2$, followed by formation of BaY_2O_5. Zero resistance of the films not having been attained at temperature < 90° K was attributed to the poor quality of the weak links (grain boundaries) of the film microstructure.

PUBLICATIONS:

DAVISON, W.W., S.G. SHYU, R.D. ROSEMAN, and R.C. BUCHANAN. Metal oxide films from carboxylate precursors. *Better Ceramics Through Chemistry, III; Proceedings Materials Research Society Symposium, 121*, 797-802 (1988). ACTC Document No. 89-03-01.

DAVISON, W.W. and R.C. BUCHANAN. ZrO_2 thin films for packaging and microelectronics applications. *Advances in Ceramics, 26* (Man F. Yan, et al., eds.) American Ceramic Society, 513-521 (1989). ACTC Document No. 90-03-02.

DAVISON, W.W. Processing and phase stability of metal carboxylate derived barium-yttrium-copper oxide thin films. Ph.D. thesis, R.C. Buchanan, advisor (1989). ACTC Document No. 90-03-03.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

R.C. Buchanan

FELLOWS:

William W. Davison Ph.D., Ceramic Engineering, November 1989

ION-PLATED COATINGS FOR EMI/EMP AND CORROSION APPLICATIONS
(Project No. 31)

by

J.M. Rigsbee, Professor of Metallurgical Engineering

PROBLEM STUDIED:

This research investigated and developed methods to regulate internal stresses at stress concentrations within structures using smart materials and smart systems. Coecptually, a smart system would sense strain development at critical locations within a structure and respond by actuating a countering strain to reduce the stress level before it becomes excessive and causes damage. This proposed effort examined single pulse and cyclic loading conditions and incorporated piezoelectric and shape memory materials as sensors and actuators. Simulated structural elements with simple stress concentrations were used as model systems.

SUMMARY OF MOST IMPORTANT RESULTS:

Coatings research centered on analysis of titanium oxy-nitride films and development of rapid deposition processing for the growth of thick TiN films. The need for rapid deposition of thick TiN coatings arised from the need to fully cover inclusions (which may serve as corrosion nucleation sites) in the substrate materials. These coatings were grown to a thickness of ~ 10 μm in < 90 minutes using a combination of titanium evaporation followed by TiN ion plating.

Analysis of the titanium oxynitride films was completed. The final results from the incorporation of oxygen into TiN showed that: 1) the titanium oxynitride corrosion current was decreased by an order of magnitude by incorporating oxygen into the films in concentrations up to 30 a/o; 2) titanium oxynitride film resistivity increased by an order of mangitude as bulk oxygen concentrations rose to ~ 30 a/o. Oxygen contents > 30 a/o resulted in extremely high and sharply increasing resistivities; 3) titanium oxynitride coatings fabricated by reactive ion plating exhibited a buld oxygen saturation of ~ 35 a/o; 4) structurally, oxygen incorporation resulted in increased microcrystallinity and/or the formation of amorphous or glassy phases without the formation of titanium oxide phases; and 5) the film surface morphology changed from a realtively coarse structure to a finer structure as the oxygen content increased.

Proposals to USA/CERL for structural applications of smart materials were developed. A day-long workshop was organized to discuss possible application of smart materials and intelligent structures for construction. These efforts were successful at initiating a program to develop a "smart roof" capable of sensing and mitigating water damage.

PUBLICATIONS:

GIVENS, J.H. and J.M. RIGSBEE. Structure and properties of titanium nitride strengthened microlaminate composites. Second International Conference on Surface Modification ASM World Materials Congress (Chicago, IL, September 1988).

RIGSBEE, J.M. Physical vapor deposition. Chapter in *Surface Modification Engineering, 1* (R. Kossowsky, ed., CRC Press, Inc., Boca Raton) vol. 1, Fundaments Aspects, 231-255 (1988).

GIVENS, J.H., W.J. CROISANT, H.S. SAVAGE, R.T. CARSON, and J.M. RIGSBEE. Characterization of titanium nitride films deposited by reactive ion plating. Ceramic Transactions 11, 59-80, *Ceramic Thick and Thin Films* (B.V. Hiremath, ed., American Ceramic Society, Columbus) (1990).

CARSON, R.T. Microchemical and electrochemical characterization of ion plated titanium nitride. M.S. thesis, J.M. Rigsbee, advisor (1990). ACTC Document No. 90-31-01.

ASSANIS, D., F. FRIEDMANN, K. WIESE, M. ZALUZEC, and J.M. RIGSBEE. A prototype thin-film thermocouple for transient heat transfer measurements in ceramic-coated combustion chambers. *Society of Automotive Engineers Technical Paper Series,* Paper 900691, (Detroit, 1990). ACTC Document No. 90-31-02.

CARSON, R.T., J.H. GIVENS, H.S. SAVAGE, Y.W. LEE, J.M. RIGSBEE, and W.J. CROISANT. Reactively ion plated TiN: Effects of RF power density on the structure and electrochemical properties. *Thin Solid Films, 204,* 285-296 (1991). ACTC Document No. 90-31-03.

FROST, R.L., A.B. DEWALT, M. ZALUZEC, J.M. RIGSBEE, B. NIELSEN, and K.G. LYNN. Slow positron annihilation spectroscopy and electron microscopy of electron beam evaporated cobalt and nickel silicides. *Journal of Vacuum Science and Technology, A 8*:4, 3210-3217 (July/August, 1990). ACTC Document No. 91-31-04.

CARSON, R.T., H.S. SAVAGE, and J.M. RIGSBEE. PVD fabrication of nanocrystalline composite materials. *Processing and Fabrication of Advanced Materials for High Temperature Applications* (V.A. Ravi and T.S. Srivatsan, eds., The Minerals, Metals and Materials Society) 361-375 (1992). ACTC Document No. 92-31-05.

CARSON, R.T., J.H. GIVENS, H.S. SAVAGE, Y.W. LEE, and J.M. RIGSBEE. Effects of oxygen on the electrical and electrochemical properties of ion plate titanium nitride. *Materials Letters, 14*, 313-317 (1992). ACTC Document 92-31-06.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

J.M. Rigsbee

FELLOWS:

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RESEARCH ASSISTANTS:

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Hong Wang	Ph.D., Materials Science, August 1993*
Matthew J. Zaluzec	Ph.D., Metallurgical Engineering, May 1991

* Expected completion date

LIGHTWEIGHT, ENERGY-EFFICIENT BUILDING MATERIAL CONCEPTS
(Project No. 32)

by

T.A. Newell, Professor of Mechanical Engineering

PROBLEM STUDIED:

Two topics related to windows and walls were investigated by this project. The first topic was related to the development of a lightweight window system that used "compound parabolic concentrators" (CPCs) to enhance solar energy gain when desired, limit solar energy gain when undesired, enhance interior daylighting, and improve window insulation properties.

The second topic consisted of developing a composite wall system that inherently provided effective insulation properties as well as other desired qualities into the structure (e.g., EMP protection or NDTE instrumentation).

SUMMARY OF MOST IMPORTANT RESULTS:

The CPC window consisted of an integral solar radiation concentrator and insulation system. A unique feature of the window system was that it was completely passive in operation, but favorably accepted solar radiation as needed for heating and/or daylighting. Research objectives consisted of the formulation of models to predict solar radiation transfer through the window, heat transfer across the window, and daylighting of the building. An optimal configuration from the simulation model results was used to design and construct a prototype window and to perform a detailed cost analysis of the window system. The prototype window was tested in order to validate simulation model predictions.

The composite wall panel investigation consisted of fabricating a wall panel that was light-weight and energy efficient. Emphasis in this research was directed toward a wall panel manufacturing strategy that could be used for interior as well as exterior panels. A specific configuration that was investigated consisted of applying a bonding material in a specified pattern between two thin sheets of material. The sheet material was separated such that the bonding material was stretched to a desired length for efficient insulation and strength properties. Research objectives consisted of formulating an analytical prediction model for the shape of the bond material as it underwent a severe deformation process. Results from that model allowed the shape of the bond material to be predicted such that a strength analysis could be performed on the panel system. Fabrication of small-scale device samples (approximately 15 cm by 30 cm) were constructed. Additional research objectives consisted of modeling strength characteristics of the panel, a literature search for determining appropriate materials for the panel system, and incorporating the effects of gravity and surface tension into the bond material deformation process.

PUBLICATIONS:

LUBBE, J.N. and T.A. NEWELL. Deformation of a fluid cylinder stretched between two flat, parallel boundaries. *ASME Journal of Fluids Engineering*, submitted, never published. ACTC Document No. 89-32-01.

LUBBE, J.M. Deformation of a cylinder of fluid stretched between two flat, parallel boundaries. M.S. thesis, T. Newell, advisor (1988).

MILLER, J.P. Investigation of a compound parabolic concentrator light panel. M.S. thesis, T. Newell, advisor (1989). ACTC Document No. 89-32-02.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

T.A. Newell

FELLOWS:

James P. Miller M.S., Mechanical Engineering, May 1989

RESEARCH ASSISTANTS:

J.N. Lubbe M.S., Mechanical Engineering, December 1988

HIGH PERFORMANCE CEMENTS
(Project No. 33)

by

J.F. Young, Professor of Material Science and Civil Engineering
R.L. Berger, Professor of Ceramic and Civil Engineering

PROBLEM STUDIED:

To investigate the structure and properties of high performance mortars as a function of cement paste properties, aggregate properties, and aggregate gradation.

SUMMARY OF MOST IMPORTANT RESULTS:

The use of a combination of Portland cement, silica fume, and high range water-reducer produced castable cement pastes of very low water contents (water:solids ~ 0.20). Compressive strength of up to 40,000 psi were possible when effective blending and dispersion of the solids were achieved to maximize packing densities.

A wide variation in the amount of silica fume could be used, but optimum quantities were 21 % by weight of cement. The chemistry of the hydration reactions was determined as a function of silica fume additions. Cement could be partially replaced by ground granulated slag without ill effects.

Addition of quartz sand to make mortars reduced strength compared to that of pure paste. The more aggregate added, the lower the strength. On the other hand, a synthetic calcined alumina aggregate strengthened the paste slightly. The effect of aggregate on strength could be predicted by simple composite models. The effective strength of the aggregate includes the influence of the cement-aggregate bond.

Up to 30 vol. % of aggregate could be added to the past before castability was lost. This is lower than the 50 - 60 vol. % that is found in the mortar fraction of very high strength concretes. Adjustments in grading could increase this figure, but reduce strength proportionally.

PUBLICATIONS:

HSIEH, H-Y. and J.F. YOUNG. Performance of DSP Mortars. American Concrete Institute Spring Convention (Boston, MA, March 1991).

YOUNG, J.F., R.L. BERGER, and T.A. BIER. Microstructure and macroscopic properties of advanced cementitious materials. Vom Werkstoffe zur Konstruktion (Festschrift Hubert K. Hilsdorf, Verlag Ernst and Sohn, Berlin, Germany, 439-464 (1990).

TOUSE, S.A., T.A. BIER, J.F. YOUNG, and R.L. BERGER. Pore structure of low porosity DSP cement. *Proceedings Materials Res. Soc. Symposium*, 137 (1989).

TOUSE, S.A. Microstructural characterization of DSP pastes. M.S. thesis, J.F. Young, advisor (1989). ACTC Document No. 89-33-01.

OTTO, G.P. Open-ended coaxial waveguides for measuring the dielectric properties of materials. M.S. thesis, W.C. Chew, advisor (1990). ACTC Document No. 90-33-02.

HSIEH, H-Y. Packing characteristics and interfacial microstructure of DSP cement mortars. M.S. thesis, J.F. Young, advisor (1992). ACTC Document No. 92-33-03.

LU, P. and J.F. YOUNG. Slag-Portland cement based DSP paste. *Journal American Ceramic Society*, accepted for publication.

LU, P., G-K. SUN, and J.F. YOUNG. Composition of DSP cement pastes. *Journal American Ceramic Society*, April 1993, in press.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

R.L. Berger
J.F. Young
Dr. P. Lu

FELLOWS:

Sara Touse-Schunkwiler	M.S., Ceramic Engineering, May 1989

RESEARCH ASSISTANTS:

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Hung-Yuan Hsieh	M.S., Civil Engineering, August 1992
Darmawan Ludirdja	Ph.D., Civil Engineering, August 1993*
Gregory P. Otto	M.S., Electrical Engineering, January 1990

* Expected completion date

ADVANCED CERAMICS FOR BUILDING CONSTRUCTION
(Project No. 35)

by

G.P. Wirtz, Professor of Ceramic Engineering
R.C. Buchanan, Professor of Ceramic Engineering
C. Dry, Professor of Architecture

PROBLEM STUDIED:

The application of advanced ceramic processing principles to the fabrication of strong lightweight ceramics for construction applications from inexpensive raw materials was studied. The overall problem was broken down into three parts, each under the direction of one of the principal investigators:

(1) Optimization of strength/weight ratio and insulating properties by the incorporation of void space into the body, both by forming a stabilized foam in the ceramic slurry before drying and firing, and by extrusion of honeycomb structures in the green state.
(2) Optimization of the strength/weight ratio by correlating microstructural and compositional variable with weight and mechanical strength by multiple regression analysis.
(3) Fabrication of strong lightweight panels and composites by low temperature phosphate bonding for structural, exterior insulation and finishing applications.

Emphasis throughout was on waste utilization and inexpensive raw materials, with minor additions of more expensive components as required for fabrication. Fly ash, bottom ash, clay, diatomaceous earth, and glass frit and fibers were the primary components of the materials studied.

SUMMARY OF MOST IMPORTANT RESULTS:

The compressive strength of fly ash bodies followed the exponential decay with porosity relationship commonly referred to as the Ryshkewitch equation:

$$\sigma = \sigma_0 e^{-\beta P} \qquad (1)$$

The pre-exponential factor in the Ryshkewitch equation, corresponding to the maximum theoretical strength for zero porosity, was nearly 600 MPa, with an exponential decay factor of -6.6, as shown in Fig. 1. Samples for Fig. 1 were prepared by casting stabilized foams for the highest porosities, casing unfoamed slips for the intermediate porosities, extruding fly ash cylinders with plasticizer added for even lower porosity, and by adding a liquid sintering aid to enhance fired density in the lowest porosity samples. All of the data fit reasonably well to the empirical equation, indicating that density was the major contributing factor to the compressive strength.

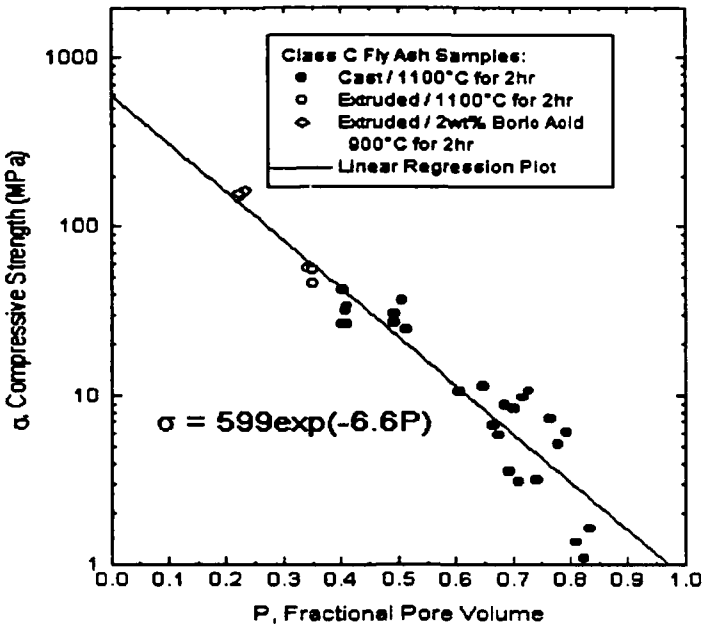

Fig. 1 Semilogarighthmic plot of compressive strength versus fractional pore volume for WBSES fly ash cylinders. Equation (1) is shown with the experimentally determined values for σ_0 and B.

To avoid this exponential decay of strength with porosity, a honeycomb structure was formed by extrusion to effect the low macroscopic density required for a high strength to weight ratio. Fig. 2 shows that for extruded honeycombs the strength decreases linearly, as opposed to exponentially, axial void space is introduced by extrusion. For such a structure, the Ryshkewitch equation must be multiplied by the area fraction of the bulk occupied by the load-bearing walls, A_w:

$$\sigma = A_w \sigma_0 e^{-\beta P_w} \qquad (2)$$

where P_w refers to the fractional porosity of the walls of the honeycomb. The area fraction in equation (2) is equal to the ratio of the macroscopic sample density to the wall density and the fractional porosity of the walls is equal to unity minus the ratio of the wall density to the theoretical density. Knowing the pre-exponential and exponential factors from equation (1), and determining the theoretical density, equation (2) may be plotted as compressive strength vs. fractional wall density for any desired value of the macroscopic density of the body. Fig. 3 shows such plots for macroscopic densities ranging from 0.5 to 1.25. Data points for the two honeycomb structures thus far produced are included in the figure. The samples with a macroscopic density of 0.98 g/cc are seen to have strengths almost exactly as predicted from equation (2). The heavier samples yielded strengths somewhat larger than theoretical. As indicated in Fig. 3, wood has an average density of about 0.5 g/cc, and a typical compressive strength of 50 MPa. To achieve this strength to weight ration in the extruded fly ash body would require a wall density of approximately 85% of theoretical, which seems well within the range of feasibility.

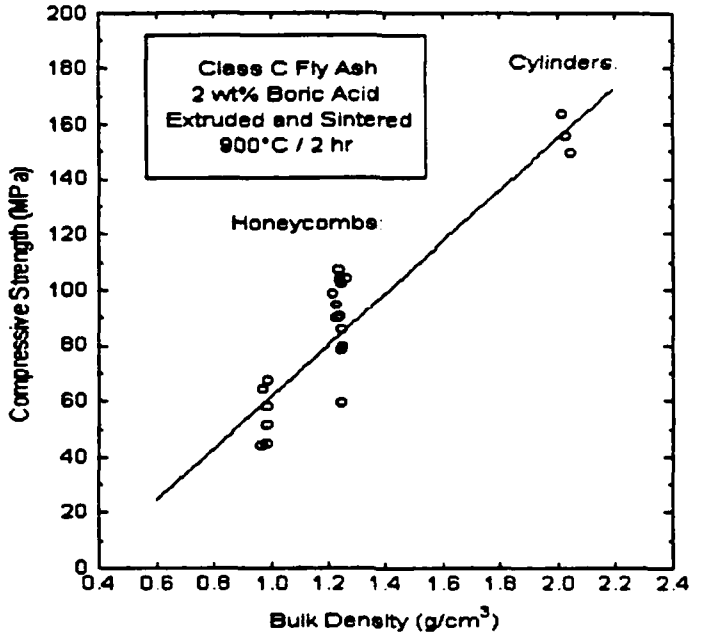

Fig. 2 Effect on compressive strength of incorporating large voids into the cross section to reduce density. The linear behavior is in contrast to the exponential behavior for random microstructural porosity.

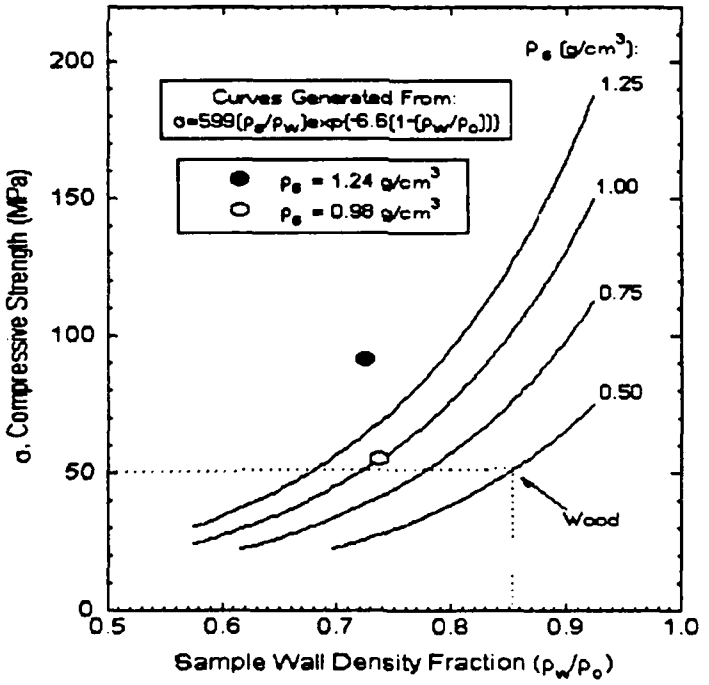

Fig. 3 Compressive strength curves plotted from equation (2). The two data points shown are for extruded honeycomb samples of WBSES fly ash with 2 wt% H_3BO_3, sintered for 2 hours at 900°C. As an example, wood has typical strength and density values of 50 MPa and 0.5 g/cm³. The same values for fly ash would require an estimated wall density fraction of about 0.85.

In the study of the optimization of the strength to weight ratio by the statistical analysis of the effects of compositional and microstructural variables of strength and density, the most significant correlation was made to the pore structure, as determined by mercury intrusion porosimetry (MIP). Fig. 4 shows a typical MIP curve of intrusion volume vs. pore diameter. The most important MIP characteristic features which are strongly related to the compressive strength are identified in the figure as: (a) the slope of the MIP curve in the region of large pores, (b) the diameter of the threshold pore, and (c) the total porosity. Equation (3) gives the predicted strength of samples in terms of these parameters.

$$\sigma = 1172e^{-0.024d}e^{-4.37P}e^{-0.45b} \qquad (3)$$

where b is the diameter of the threshold pore, P is the total porosity, and d is the slope of the MIP curve in the region of large pores. Comparing the experimental parameters of equation (3) with those of equation (2) determined from Fig. 1, it is seen that the maximum theoretical strength for this composition is about double that of the fly ash, with a smaller exponential decay factor, the major component of which is still the total porosity, but with significant contributions from the pore size distribution factors.

Through this statistical analysis, optimization resulted in strengths of 35 to 75 MPa with densities in the range of 0.9–1.0 g/cc. The optimized composition corresponded to a mixture of kaolin, diatomaceous earth and frit, in the ratio of 40:40:20.

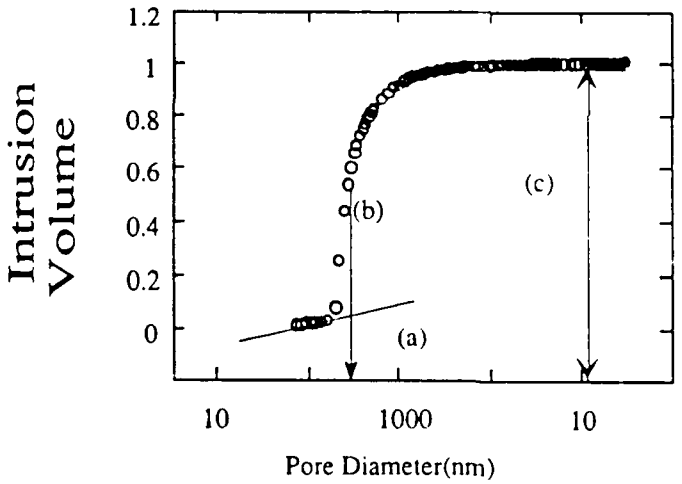

Fig. 4 Intrusion volume vs. pore diameter for mercury intrusion porosimetry of kaolin, diatomaceous earth, glass frit fired compositions.

For Exterior Insulation and Finish Systems (EIFS), ash material has been developed for a sandwich panel, exterior insulation and a lightweight building material. Fly ash/alumina/phosphoric acid compositions using hollow fly ash spheres (floaters) showed a compressive strength of 5–7 MPa, density of 0.52 g/cc and insulative value of R 1.27 (0.11 W/mK). The microstructure was characterized by large discontinuous spherical pores, each corresponding to a single hollow fly ash particle. This material is proposed for use as the center of structural sandwich panels and/or for exterior applied insulation. Additional compressive and impact strength can be imparted by stronger (20 MPa) heavier (1.5 g/cc) sintered bottom ash/phosphoric acid materials used as the external surface in a sandwich panel configuration.

PUBLICATIONS:

DAVISON, W.W., W.G. SHYU, and R.C. BUCHANAN. High T_c superconducting films from metalloorganic precursors. *Mat. Res. Soc. Symposium Proceedings, 99*, 289-292.

DAVISON. W.W. and R.C. BUCHANAN. Microstructure and phase stability of metal carboxylate-derived $Ba_2YC_{u3}O_{7-x}$ Thin films. *Ceramic Transactions 13, Superconductivity and Ceramic Superconductors* (K.M. Nair and E.A. Giess, eds., American Ceramic Society, Westerville, OH) 565-578 (1990).

DAVISON, W.W., S.G. SHYU, R.D. ROSEMAN, and R.C. BUCHANAN. Metal oxide films from carboxylate precursors. *Better Ceramics Through Chemistry, III; Proceedings Materials Research Society Symposium, 121* 797-802 (1988).

DAVISON, W.W. and R.C. BUCHANAN. ZrO_2 thin films for packaging and microelectronics applications. *Advances in Ceramics, 26* (Man F. Yan, et al., eds.) American Ceramics Society, 513-521 (1989).

DRY, C. Structure by the time release of internal chemicals. Conference on Advances in Cementitious Materials, American Ceramic Society, Inc., and National Institute of Standards and Technology, Gaithersburg, MD, July 23-26, 1990.

DRY, C. Phosphate bonded and sintered fly ash, and bottom ash for lightweight construction panels. 92nd Annual Meeting, American Ceramics Society, Dallas, Texas, April 22-26, 1990.

PARK, T. and R.C. BUCHANAN. Fabrication of light weight ceramics for structural application using sol-gel processing. *92nd Annual Meeting, American Ceramics Society*, Dallas, TX, April 22-26, 1990. American Ceramics Society Paper No. SV-135-90.

BIGGAR, J. and C. DRY. Phosphate bonding of industrial waste. Annual Meeting, American Ceramic Society (Indianapolis, IN, April 23-27, 1989) American Ceramics Society Paper No. 13-T-89.

DRY, C. Building materials which evolve and adapt over time — use of encapsulation technology and delayed reactions. *Proceedings of the Architectural Research Centers Consortium (ARCC) Conference '88*, University of Illinois School of Architecture, Champaign, IL, November 13-15, 1988.

WYLDER, J.R. and G.P. WIRTZ. Foaming fly ash for production of construction material, *American Ceramic Society, Inc. 91st Annual Meeting* (Indianapolis, IN, April 1989) Paper No. 13-M-89.

ANDERSON, M.W. and G.P. WIRTZ. Incorporating the Sol-Gel process into the manufacture of lightweight building materials. *91st Annual Meeting and Exposition of the American Ceramic Society* (Indianapolis, IN, April 1989) Paper No. 14-M-89. ACTC Document No. 89-35-02. presentation

DRY, C. New cementitious building materials which are more durable, Architectural Research Centers Consortium '88 Conference (Champaign, IL, November 13-15, 1988).

DRY, C. Alteration of permeability by the timed release of internal chemicals, Conference on Advances in Cementitious materials, American Ceramic Society, Inc., and National Institute of Standards and Technology (Gaithersburg, MD, July 1990).

DRY, C.M. Durability of sandwich panels made from phosphate bonded/ sintered fly ash and bottom ash. *Proceedings of the Ninth International Ash Use Symposium*, American Coal Ash Association, Hyatt Orlando, Florida, January 22-25, 1991, Electric Power Research Institute (EPRI) (Research Reports Center), Box 50490, Palo Alto, CA 94303, publisher, 1991, pp. 77-1 to 77-21.

DRY, C.M. Structural sandwich panels made from fly ash and bottom ash sintered and phosphate bonded. International Symposium on the Performance Characteristics and Mechanical Properties of High Volume Fly Ash Concretes, Committee A2E01, Transportation Research Board (Washington, January 1991).

PARK, T. and R.C. BUCHANAN. Rheology effects on strength and density relationship in light weight ceramics. *91st Annual Meeting, American Ceramic Society* (Indianapolis, IN, April 1989) Paper No. 48-SIV-89. ACTC Document No. 89-35-04.

ANDERSON, M.W. Incorporating the sol-gel process into the manufacture of lightweight fly ash building material. M.S. thesis, G.P. Wirtz, advisor (1989). ACTC Document No. 89-35-05.

WYLDER, J.R. Processing and characterization of a foamed fly ash construction material. M.S. thesis, G.P. Wirtz, advisor (1989). ACTC Document No. 89-35-06.

PARK, T. Fabrication of lightweight ceramics through casing process at low sintering temperature. Ph.D. thesis, R.C. Buchanan, advisor (1992). ACTC Document No. 92-35-07.

DeFord, H.D. and G.P. Wirtz. Extrusion of lightweight construction material from fly ash. *Ceramic Engineering Science Proceedings 14*:1 and 2, 298-308 (1993).

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

R.C. Buchanan
C. Dry
G.P. Wirtz

FELLOWS:

Michael W. Anderson	M.S., Ceramic Engineering, October 1989
John P. Biggar	M.S., Architecture, August 1989
William W. Davison	Ph.D., Ceramic Engineering, November 1989

RESEARCH ASSISTANTS:

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Mark E. Bartos	M.Arch., Architecture, May 1992
Jeffrey H. Boy	Ph.D., Ceramic Engineering, August 1991
Jaya Darda	M.S., Landscape Architecture, December 1989
Kim M. Deason	M.S., Theoretical and Applied Eng., January 1990
Harvey D. DeFord	Ph.D., Ceramic Engineering, December 1993*
Christina M. Eales	M.Arch., Architecture, May 1991
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	M.U.P., Urban Planning, May 1991
Thomas Houck	M.Arch., Architecture, May 1990
Todd Jesperson	M.Arch., Architecture, August 1993*
Jill M. Kustom	M.Arch., Architecture, December 1993*
Eric Lawson	M.Arch., Architecture, May 1989
David A. Mitchell	M.Arch., Architecture, January 1995*
	M.S., Civil Engineering, January 1995*
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	Ph.D., Ceramic Engineering, May 1993*
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Naomi Voegtli	M.S., Computer Science, August 1991
Dennis Wall	
J.R. Wylder	M.S., Ceramic Engineering, August 1989
M. Yazbec	M.Arch., Architecture, May 1991

* Expected completion date

THRUST AREA

COMPUTER-AIDED CONSTRUCTION

A FLEXIBLE MANUFACTURING SYSTEMS APPROACH TO CONSTRUCTION AUTOMATION

(Project No. 36)

by

S.G. Kapoor, Professor of Mechanical and Industrial Engineering
U.S. Palekar, Professor of Mechanical and Industrial Engineering

PROBLEM STUDIED:

This project was concerned with the application of flexible manufacturing techniques to improve the productivity of precast concrete production.

SUMMARY OF MOST IMPORTANT RESULTS:

The project identified aspects of the precast concrete manufacturing process which could benefit from automation and standardization. A computer simulation was developed to study the bottlenecks and inefficiencies of existing plants and to test alternate manufacturing strategies. Experiments with the simulation model identified the form construction process, the rebar cage assembly process and the material handling system as primary areas of concern. The project involved a study of each of these areas to improve the safety and reliability of operations.

To improve the form construction process a group technology approach was used to classify products with similar geometries.. A modular formwork system was designed which could be assembled for a variety of different products. Changes in the design of the casting bed have been suggested to make the casting process more flexible an for more efficient use of the bed. To further increase the utilization of the casting bed without sacrificing safety a diagnostic monitoring system was also proposed.

A robotic cell for the automated assembly of rebar cages was developed. A representation scheme that permits the automatic generation of code for the control of the robotic cell was developed and implemented.

Research on the improvement of material handling systems was concentrated primarily on the planning of routes for material handling devices such as robotic cranes and automated guided vehicles in a multi-device environment to avoid collisions and minimize response time. Several novel algorithms were devised which efficiently plan paths for several vehicles. The techniques devised in this research can be used for planning paths for single or multiple devices co-operating to carry large loads in obstacle strewn space.

PUBLICATIONS:

KAPOOR, S.G. and M.D. WAVERING. A robotic assembly cell for precast reinforcement cages. Sixth International Symposium on Automation and Robotics in Construction. (San Francisco, CA, June 1989).

HUANG, J-F. U.S. PALEKAR, and S.G. KAPOOR. A labeling algorithm for the navigation of automated guided vehicles. *Advances in Manufacturing Systems Eng. PED-Vol. 37*, 181-194, WAM-ASME (1989). ACTC Document No. 89-36-01.

WAVERING, M.D. A flexible manufacturing systems approach for integrated automation of building construction. M.S. thesis, S.G. Kapoor, advisor (1989). ACTC Document No. 89-36-02.

KAPOOR, S.G., U.S. PALEKAR, and M. WAVERING. A group technology based modular formwork system for precast concrete. *Proceedings Sixth Computer Aided Production Engineering Conference* (London, England, November 1990) 221-225 (1990). ACTC Document No. 91-36-03.

HUANG, J-F. and U.S. PALEKAR. Performance evaluation of a routing algorithm for AGV systems. *Transactions of NAMRC, XIX*, 345-351 (1991). ACTC Document No. 91-36-04.

HUANG, J-F. Load volume considerations in the collision free route planning of material handling devices in FMS. Ph.D. thesis, U.S. Palekar, advisor (1992). ACTC Document No. 92-36-05.

HUANG, J-F. and U.S. PALEKAR. Geometry considerations in the routing of automated guided vehicles. *Transactions NAMRI/SME XX*, 369-378 (1992). ACTC Document No. 92-36-06.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

S.G. Kapoor
U.S. Palekar

FELLOWS:

Matthew D. Wavering	M.S., Mechanical Engineering, May 1989

RESEARCH ASSISTANTS:

Jiufen Huang	Ph.D., Industrial Engineering, May 1992
Kurt Doner	M.S., Civil Engineering, January 1989

A UNIFIED KNOWLEDGE-BASED MODEL FOR BUILDING DESIGN AND CONSTRUCTION
(Project No. 37)

by

L.A. Lopez, Professor of Civil Engineering
J.H. Garrett, Jr., Professor of Civil Engineering

PROBLEM STUDIED:

The purpose of this project was to develop an object-oriented data model for representing the information generated and needed during the life-cycle of a building project. The objective was to provide a data model that would support the conceptual design phase, detailed design phase and the construction planning phase, thus providing a medium by which to integrate these various phases. This model has to be more than just a model of the geometry of the structure; it must identify the functional, spatial, and physical aspects of the structure. How this model could be employed to support the various stages of the construction process was also investigated; specifically, this model was used to bring downstream construction cost and time estimations into the early stages of the conceptual design process.

SUMMARY OF MOST IMPORTANT RESULTS:

One important result from this research is that we discovered that one cannot have one single schema of objects from which one creates an instance to model a component or system in a building. One needs several different schemes for the various aspects of a building: functional, spatial, physical. Any component or system in a building is then composed of attributes inherited from classes from each of these different schemes. The model itself that was developed as part of this work is an important contribution; the model was composed of instances from three different hierarchies of objects for functional, spatial and physical aspects of a building. Since publication of this model, it has been referenced and extended by other researchers. A prototype system for performing construction cost and time estimation using this object-oriented model of a building was created in a follow-up project to this project; this prototype system is also a very important contribution. This latter work also extended the object-oriented building model to include construction planning related information, which also was an important contribution.

PUBLICATIONS:

ELAM, S.L. Knowledge based approach to checking designs for conformance with standards. Ph.D. thesis, L.A. Lopez, advisor (1988). ACTC Document No. 89-37-01.

GARRETT JR., J.H., J. BASTEN, J. BRESLIN, and T. ANDERSON. An object-oriented model for building design and construction. *Computer Utilization in Structural Engineering, Proceedings 1989 ASCE Conference* (James K. Nelson, ed.) 332-341 (1989). ACTC Document No. 89-37-02.

GARRETT, JR., J.H., J. BASTEN, and J. BRESLIN. An object-oriented environment for representing building design and construction data. Technical Report No. 89-37-04, Advanced Construction Technology Center, University of Illinois, Urbana, IL 1989.

LOPEZ, L.A., S. ELAM, and K. REED. Software concept for checking engineering designs for conformance with codes and standards. *Engineering with Computers, 5*, 63-78 (1989). ACTC Document No. 89-37-05.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

J.H. Garrett, Jr.
L.A. Lopez

FELLOWS:

John Breslin	M.S., Civil Engineering, May 1989
Steve Elam	Ph.D., Civil Engineering, October 1988

RESEARCH ASSISTANTS:

J. Basten	M.S., Civil Engineering, January 1990

HANDLING CONSTRAINTS IN AN OBJECT-ORIENTED DATABASE
(Project No. 41)

by

G.G. Belford, Professor of Computer Science

PROBLEM STUDIED:

The overall goal of this project was the design of a database management system able to support the construction process. A construction database must provide both horizontal and vertical integration of the construction activity — horizontal meaning the support of multiple users that access the data for various purposes at the same time, and vertical meaning the support of the successive phases of a construction project over time, from the original building design through planning and materials procurement and actual construction to the creation of as-built drawings and building maintenance. Preliminary study led us to decide on the object-oriented data model as the most appropriate model for construction data, and the down-sizing of the project to one thesis caused us to limit ourselves to the problem of determining the best way to represent and enforce constraints on data values, especially in the case of logically linked data object instances, in an object-oriented database.

SUMMARY OF MOST IMPORTANT RESULTS:

In an object-oriented database, constraints may be represented in two basic ways, either as code embedded in the data objects or as separate class hierarchy of constraint objects. Each has advantages and disadvantages, depending upon the type of constraint and the structure of the data. We have concluded that a system should support both modes of constraint representation. We have demonstrated the feasibility of this dual approach by designing a set of compatible protocols for constraint checking and maintenance.

PUBLICATIONS:

BELFORD, G.G. and A.L. SANTONE. Object-oriented databases for construction data. *Proceedings 22nd Hawaiian International Conference on System Sciences, Computer Society Press, II* (Kona, Hawaii, January 1989) 559-568. ACTC Document No. 89-41-01.

MUROGA, E. and G.G. BELFORD. Designing a constraint checking system for an object-oriented database. IFIP Fourth TCZ Working Conference on Database Semantics, Windmere, England, July 1990. ACTC Document No. 90-41-02.

MUROGA, E. Constraint models for an object-oriented database. Ph.D. thesis, G.G. Belford, advisor (1990). ACTC Document No. 90-41-03.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

G.G. Belford

FELLOWS:

Craig Murphy resigned fellowship

RESEARCH ASSISTANTS:

Muroga, Eisuke Ph.D., Computer Science, May 1990

DESIGN FOR AUTOMATED CONSTRUCTION
(Project No. 42)

by

L.T. Boyer, Professor of Civil Engineering

PROBLEM STUDIED:

The objective of the research was to identify the factors that determine the amenability of construction tasks to automation and develop a quantitative method to evaluate the Automated Constructability of building designs. The developed method should identify the characteristics of a design and the associated machine requirements necessary to perform construction of the design.

The research also sought to determine the advantages and limitations of each of several sensor technologies in terms of function, environment and accuracy limitations.

SUMMARY OF MOST IMPORTANT RESULTS:

The reviewed factors which impact the automated constructability of a specific design included material and geometric characteristics. The material characteristics included were rigidity/viscosity of the materials, the amount of adhesion and friction, the weight of the individual components, fastening types, stability during construction, and the size of components. The geometric characteristics included the spatial relationship among components, tolerances of dimensions and component topology as generated by reverse construction processes. Machine requirement were compared to machine capabilities to determine if specific construction tasks can be performed by automated equipment.

Sensor strategies were developed to optimize the use of several sensor technologies on the basis of each sensor's performance.

PUBLICATIONS:

GOODIN, A.C. and L.T. BOYER. Identification and measurement technologies applicable to construction. Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction (Haifa, Israel, June 1987).

GATTON, T.M. and L.T. BOYER. Designing for construction automation. Architectural Research Center Consortium Conference, sponsored by the Department of Architecture, (University of Illinois at Urbana-Champaign, IL, November 1988).

BOYER, L.T. and T.M. GATTON. Design for automated construction. *Proceedings Fifth International Symposium on Robotics in Construction, 2* (Tokyo, Japan, June 1988) 679-688 (1988).

GATTON, T.M. Designing for construction automation: Advanced automation technologies for computer integrated construction. Ph.D. thesis, L.T. Boyer, advisor (1991). ACTC Document No. 91-42-01.

GOODIN, A.C. A maturity-based system for *in-situ* evaluation of concrete. Informal report. ACTC No. 91-42-02.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

L.T. Boyer

FELLOWS:

Anthony Goodin	M.S., Civil Engineering, August 1988
Robert Twardock	M.S., Civil Engineering, January 1988

RESEARCH ASSISTANTS:

Thomas M. Gatton	Ph.D., Civil Engineering, October 1991
Brian Ramsey	M.S., Civil Engineering, January 1987

AUTOMATED DESIGN SYNTHESIS FOR COMPUTER-AIDED CONSTRUCTION
(Project No. 44)

by

S.C-Y. Lu, Professor of Mechanical Engineering

PROBLEM STUDIED:

Problem 1. Higher quality and lower cost construction can be achieved by considering and incorporating life-cycle concerns during all phases of the construction engineering process. In this research, design methodologies and computer-aided design tools were developed which support communication and cooperation among construction engineering participants so that life-cycle concerns can be expressed and integrated during the construction engineering process.

Problem 2. In conventional design practice, engineers typically record only final, "finished" design descriptions. This research focused on the representation of the design process which results in final design descriptions.

SUMMARY OF MOST IMPORTANT RESULTS:

Problem 1. Computer methods for both analysis and synthesis of geometric tolerance specifications were developed to support the design of assemblies. The representation and computational methods were developed within a framework for tolerance synthesis which includes seven interconnected computing tasks. To demonstrate the improved facilities for tolerance specification which result from the integration and interaction within the framework, a prototype computing environment, CASCADE-T, was developed.

Problem 2. A prototype computer-based design environment, called AIDEMS, was built and used to demonstrate the practice of Design Evolution Management in example design process. The design environment provides designers a platform for interactive expression of their design strategies and tactics and uses AI programming techniques for semi-automated resource scheduling, execution of design revisions, exploration of design alternatives, and generation of explanations.

PUBLICATIONS:

THOMPSON, J.B. and S.C-Y. LU. Design evolution management: A methodology for representing and using design rationale. *Proceedings Second International ASME Conference on Design Theory and Methodology* (Chicago, Illinois, September 1990) 185-191 (1990).

GARRETT, Jr., J.H., S.C-Y. LU, J.B. THOMPSON, and A.E. HERMAN. Applications of artificial intelligence techniques to engineering design at the University of Illinois at Urbana-Champaign. *Proceedings of AIENG90 1* (Boston, MA, July 1990) 261-280 (1990).

THOMPSON, J.B. and S.C-Y. LU. A design model to support design evolution management. AAAI-90 Workshop on Concurrent Engineering (Boston, MA, July-August 1990).

WILHELM, R.G. and A.E. HERMAN. Computer aids for engineering design decisions: a simple contradiction handler for IDEEA applications. Technical Report, Knowledge-Based Engineering Systems Research Laboratory, University of Illinois at Urbana-Champaign (1991).

WILHELM, R.G. and S.C-Y. LU. Tolerance synthesis to support concurrent engineering. *Annals of CIRP, 41*:1, 197-200 (1992).

GUSTAFSON, B.K. Development of localized planner for AI-based robot task planning system. M.S. thesis, S.C-Y. Lu, advisor (1986).

LU, S.C-Y. and J.B. THOMPSON. A distributed artificial intelligence approach to integrated engineering design. *Proceedings First International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems* (Tullahoma, TN, June 1988) 438-446 (1988).

LU, S.C-Y. Knowledge processing for engineering automation: A summary of current research in knowledge-based engineering research laboratory. NSF Grantees Conference on Manufacturing Systems Research (Berkeley, CA, January 1988). ACTC Document No. 89-44-01.

THOMPSON, J.B. and S.C-Y. LU. Representing and using design rationale in concurrent product and process design. *Proceedings ASME Symposium on Concurrent Product and Process Design* (San Francisco, CA, December 1989) 109-115. ACTC Document No. 89-44-02.

LU, S.C-Y. and R.G. WILHELM. Automating tolerance synthesis: A framework and tools. *SME Journal of Manufacturing Systems, 10*:4, 279-296 (1991). ACTC Document No. 89-44-03.

LU, S.C-Y., S. SUBRAMANYAM, J.B. THOMPSON, and M. KLEIN. A cooperative product development environment to realize the simultaneous engineering concept. *Proceedings ASME International Computers in Engineering Conference 1* (Anaheim, California, June 1989) 9-18 (1989). ACTC Document No. 89-44-04.

WILHELM, R.G. and S.C-Y. LU. Tolerance primitives for composition and synthesis. *Transactions of the North American Manufacturing Research of SME*, 366-370 (1990). ACTC Document No. 90-44-05.

LU, S.C-Y. and R.G. WILHELM. Applying constraint-based reasoning to geometric tolerancing. *Proceedings International Conference in Artificial Intelligence in Engineering, 1*, 37-54 (1990). ACTC Document No. 90-44-06.

WILHELM, R.G. and S.C-Y. LU. Tolerances and function in concurrent product and process design. *Transactions of the North American Manufacturing Research Institute of SME*, 357-363 (1991). ACTC Document No. 91-44-07.

THOMPSON, J.B. Design evolution management: A design methodology for representing and utilizing design rationale. Ph.D. thesis, S.C-Y. Lu, advisor (1990). ACTC Document No. 91-44-09.

WILHELM, R.G. Computer methods for tolerance synthesis. Ph.D. thesis, S.C-Y. Lu, advisor (1991). ACTC Document No. 91-44-10.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

S.C-Y. Lu

FELLOWS:

James B. Thompson	*Ph.D., Mechanical Engineering, October 1990*
Bradley K. Gustafson	M.S., Mechanical Engineering, 1987

RESEARCH ASSISTANTS:

Robert G. Wilhelm	Ph.D., Mechanical Engineering, January 1992

AN OBJECT-ORIENTED MODEL FOR INTEGRATING DESIGN AND CONSTRUCTION
(Project No. 48)

by

J.W. Melin, Professor of Civil Engineering

PROBLEM STUDIED:

The objective of this research is to develop a project model such that integrated construction schedules and cost estimates are generated from an object-oriented design description. The project model consists of an object-oriented d
representation of design and construction objects, and the required knowledge-based construction management modules operating or reasoning with these objects.

SUMMARY OF MOST IMPORTANT RESULTS:

One important result from this research is the project model which accepts a set of preliminary design parameters and generates an integrated schedule and cost estimate. The project model allows for interactive and iterative changes of design and construction plans, and allows for the evaluation of the impacts on the schedule and on the cost estimate due to these changes.

PUBLICATIONS:

ECHEVERRY, D., C.W. IBBS, and S. KIM. A knowledge based approach to support the generation of construction schedules. *Proceedings International Conference on Application of Artificial Intelligence Techniques for Civil and Structural Engineers* (London, England, September 1989) 115-122 (1989). ACTC Document No. 89-48-01.

GARRETT, JR., J.H. and N-J. YAU. Issues in representing engineering design decisions for support of concurrent engineering. *Proceedings of the MIT-JSME Workshop on Cooperative Product Development* (D. Sriram, R. Logcher, and S. Fukuda, eds.) (Massachusetts Institute of Technology, Boston, MA. November 1989) 492-500 (1989). ACTC Document No. 89-48-02.

YAU, N-J., J.W. MELIN, J.H. GARRET, JR., and S. KIM. An environment for integrating building design, construction scheduling, and cost estimating. *Proceedings ASCE Seventh Conference on Computing in Civil Engineering and Symposium on Data Bases* (Washington, D.C., May 1991) 222-232 (1991). ACTC Document No. 91-48-03.

ECHEVERRY, D., C.W. IBBS, and S. KIM. Sequencing knowledge for construction scheduling. *ASCE Journal of Construction Engineering and Management, 117*:1, 118-130 (1991). ACTC Document No. 91-48-04.

YAU, N-J., J.W. MELIN, J.H. GARRETT, JR., and S. KIM. Integrating the processes of design, scheduling, and cost estimating within an object-oriented environment. *Proceedings Construction Congress '91: Preparing for Construction in the 21st Century* (Cambridge, MA, April 1991) 342-347 (1991). ACTC Document No. 91-48-05.

YAU, N-J. An object-oriented project model for integrating building design, construction scheduling, and cost estimating for mid-rise construction. Ph.D. thesis, J.W. Melin, advisor (1992). ACTC Document No. 92-48-06.

ECHEVERRY, D. Factors for generating initial construction schedules. Ph.D. thesis, C. William Ibbs, advisor (1991). ACTC Document No. 91-48-07.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

J.W. Melin

RESEARCH ASSISTANTS:

Diego Echeverry	Ph.D., Civil Engineering, May 1991
F. Grobler	Ph.D., Civil Engineering, October 1988
A. Hassanein	Ph.D., Civil Engineering, January 1990
Zafar A. Nomani	M.S., Civil Engineering, August 1989
Nie-Jia Yau	Ph.D., Civil Engineering, March 1992

HORIZONTAL CONSTRUCTION — IMPROVED FACILITY DESIGN, CONSTRUCTION, AND REHABILITATION
(Project No. 51)

by

E.J. Barenberg, Professor of Civil Engineering
M.R. Thompson, Professor of Civil Engineering

PROBLEM STUDIED:

Large-scale transportation construction projects (e.g. airfield and highway pavements) cut across many different soils. It is helpful to have a quick and economical method for estimating subgrade soil moduli for pavement design or other horizontal construction related purposes. Numerous studies have indicated that U.S. Department of Agriculture Soil Conservation Service (SCS) pedologic soil series classification (as used in a SCS County Soil Report MAP) is an appropriate procedure for characterizing the engineering properties of surficial soils. In this study, the potential use of pedologic soil series classification for characterizing and estimating the resilient modulus (E_{Ri}) of fine-grained subgrade soils was considered.

SUMMARY OF MOST IMPORTANT RESULTS:

It was demonstrated that SCS pedologic soil series classification can be utilized to characterize and estimate the resilient modulus of fine-grained subgrade soils. The use of soil series - subgrade E_{Ri} data based on an analysis of Falling Weight Deflectometer (FWD) deflections can greatly expedite and simplify the establishment of (E_{Ri}) values for pavement analysis and design and similar types of horizontal construction activities. If data are not available for a particular soil series, soil series - E_{Ri} data can be easily developed by conducting FWD tests on existing flexible pavements constructed in locations where the soil series is present.

PUBLICATIONS:

IOANNIDES, A.M., E.J. BARENBERG, and J.A. LARY. Interpretation of falling weight deflectometer results using principles of dimensional analysis. *Proceedings of Fourth International Conference on Concrete Pavement Design and Rehabilitation* (Purdue University, April 1989) 231-247 (1989). ACTC Document No. 89-51-01.

BARENBERG, E.J. and A.M. IOANNIDES. Structural evaluations of concrete slabs using falling weight deflectometer results. Interim Technical Report, Advanced Construction Technology Center (1989). ACTC No. 89-51-02.

WILSON, T. and M.R. THOMPSON. Pedologic soil series — resilient moduli relations. Interim Technical Report, Advanced Construction Technology Center (1989). ACTC Document No. 89-51-03.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

E.J. Barenberg
M.R. Thompson

RESEARCH ASSISTANTS:

Kenneth Dowd	M.S., Civil Engineering, January 1989
Thomas Wilson	M.S., Civil Engineering, January 1989

MULTICAST COMMUNICATIONS
(Thesis Scale)

by

J. Liu, Professor of Computer Science

PROBLEM STUDIED:

This project addressed the problem of how to effectively support communication between processes on different computers, monitoring sensors, and controlling terminal devices and actuators in an integrated computer-aided construction environment. Data to be transmitted in this environment are typically heterogeneous and isochronous, including real-time telemetry, digitized voice and video, facsimile, graphics, and messages. Invariably, reliable multicast capability must be provided. Among the problems addressed are multicast routing of isochronous data in bus-based networks and effective use of multichannel networks.

SUMMARY OF MOST IMPORTANT RESULTS:

For several classes of network topologies, efficient algorithms for routing and switching multicast messages were developed. Performance data showed that these algorithms perform well in terms of bandwidth consumption, packet delay, and the size of state information required to forward packets. With the advent of very high bandwidth optical fibers has come an increased interest in multichannel networks. Multichannel networks require that nodes be equipped with either multiple transceivers or tunable transceivers. A variety of partially-connected interconnection patterns, in conjunction with particular access methods, have been proposed for multichannel networks. The effect of multicast communication in the design, operation and performance of multichannel networks were studied.

PUBLICATIONS:

McKINLEY, P.K, and J. LIU. Multicast routing in bus-based computer networks. *Proceedings IEEE Computer Networking Symposium* (Washington, D.C., April 1988) 277-287 (1988).

McKINLEY, P.K. and Y. OFEK. Resource sharing in a synchronous optical hypergraph. *Proceedings Symposium on the Simulation of Computer Networks* (Colorado Springs, CO, August 1987) 159-169 (1987).

McKINLEY, P.K. Multicast routing in spanning bus hypercubes. *Proceedings International Conference on Parallel Processing* (St. Charles, IL, August 1988) 204-211 (1988).

LO, T.M. Data modeling of three-dimensional objects. M.S. thesis, J. Liu, advisor (1989).

McKINLEY, P.K. and J. LIU. Group communication in interconnected bus networks. Phoenix Conference on Computers and Communications (Scottsdale, AZ, March 1989).

McKINLEY, P.K. Group communication in bus-based computer networks. Ph.D. thesis, J. Liu, advisor (1989). ACTC Document No. 89-LIU-01.

McKINLEY, P.K. and J. LIU. Multicast trees in bus-based networks. *Proceedings Phoenix Conference on Computers and Communications* (Scottsdale, AZ, March 1989) 171-177 (1989).

McKINLEY, P.K. and J. LIU. Multicast trees in bus-based networks. *ACM Communications 33*:1, 29-42 (1990). ACTC Document No. 90-LIU-02.

McKINLEY, P.K. and J. LIU. Group communication in multichannel networks with staircase interconnection topologies. *Proceedings ACM Sig-Comm 89 Symposium Communication Architectures and Protocols* (Austin, TX, September 1989) 170-181 (1989). ACTC Document No. 89-LIU-04.

RAJAGOPALAN, B. and P.K. McKINLEY. A token-based protocol for reliable ordered multicast communication. *Proceedings Eighth Symposium on Reliable Distributed Systems* (Seattle, WA, October 1989) 84-93 (1989). ACTC Document No. 89-LIU-05.

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

J. Liu

FELLOWS:

P.K. McKinley Ph.D., Computer Science, 1989

RESEARCH ASSISTANTS:

Tak Ming Lo M.S., Computer Science, 1989

THRUST AREA

SPECIAL TECHNOLOGIES

IN SITU SOIL REINFORCEMENT—SOIL NAILING
(Project No. 52)

by

J.H. Long, Professor of Civil Engineering
E.J. Cording, Professor of Civil Engineering

PROBLEM STUDIED:

The purposes of this research program were to develop a better understanding of the behavior of insitu reinforced soil, and to develop and evaluate methods of analyses for predicting the deformation and failure of insitu reinforced soil. Emphasis was directed toward soil nailed walls as the type of insitu reinforcement technique. Results from analytical studies, numerical studies, and small-scale, large scale, and full-scale tests were analyzed to isolate, qualify, and quantify important features that affect the performance of soil nailed walls.

SUMMARY OF MOST IMPORTANT RESULTS:

Large, Model-Scale Test Facility. A major accomplishment of this project was the conception, design, construction, and use of the a large, model-scale test facility. The facility was used to study the behavior of large, model-scale soil nailed walls during construction. The facility provided the unique opportunity to construct, test, and monitor the performance of soil nailed walls in environmental conditions that can only be provided in the laboratory. The physical size of the model tests has never been attempted. Results of the model tests demonstrate the construction details are of paramount importance.

Theoretical Studies Associated with Soil Nailing. Two approaches for analyzing soil nailed walls were developed. One method relies on a limit approach, while the other employs a soil model and Finite Element approach.

A limit procedure for determining stability of slopes was modified to assess the stability of soil nailed walls. Further modifications, and a "method of superposition" procedure were developed to allow for wall stability estimates, as well as reasonable estimates of tensile loads in soil nailed walls. Several fundamental studies were conducted to assess effects of 1) various assumptions required for conducting limit-equilibrium analyses, 2) geometrical shapes of failure surfaces, 3) and wall geometry and material properties.

Limit analyses developed for this project compared very favorably with measured nail forces for the CEBTP full-scale soil nailed wall in France. Additional investigations of other full-scale soil nailed walls reported in the literature indicate the method developed for this research predicts maximum nail forces well.

A finite element computer program employing a sophisticated elasto-plastic soil model was also developed and verified. The numerical analysis models both wall construction and soil behavior realistically. Excavation of the soil and placement of the nails is modelled for every row of nails installed. Additionally, the soil-structure interface between the soil and nail, and the facing of the soil nailed wall, is modelled. Parametric studies were conducted and reported in the thesis by M. E. Salama.

Full-Scale Field Tests. During the analytical and laboratory portions of this research effort, the principal investigators cooperated closely with a contractor that builds soil nailed walls. The cooperation resulted in development of a unique way to monitor loads in soil nails, and allowed for the collection of data on the behavior of a full scale soil nailed wall. Results were used to confirm the validity of the analytical and numerical methods developed.

PUBLICATIONS:

LONG, J.H., W.F. SIECZKOWSKI, E. CHOW, and E.J. CORDING. Stability analyses for soil nailed walls. Specialty Conference on the Design and Performance of Earth Retaining Structures, ASCE (Ithaca, NY, June 1990).

SIECZKOWSKI, W.F. Soil nailing — *in situ* soil reinforcement. M.S. thesis, J.H. Long, advisor (1989). ACTC Document No. 89-52-01.

SALAMA, M.E. Analysis of soil nailed retaining walls. Ph.D. thesis, E.J. Cording, advisor (1991). ACTC Document No. 92-52-02.

HENDRON, M.A. Behavior and analysis of large-scale model soil nailed retaining walls in sand. Ph.D. thesis, J.H. Long, advisor (1993*).

LARSON, G.E. Computer modeling of tied-back walls. Ph.D. thesis, J.H. Long, advisor (1993*).

PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES AWARDED:

FACULTY:

E.J. Cording
J.H. Long

FELLOWS:

Michael A. Hendron	Ph.D., Civil Engineering, 1993*
Gregg Larson	M.S., Civil Engineering, May 1988
	Ph.D., Civil Engineering, 1993*
William F. Sieczkowski	M.S., Civil Engineering, May 1989

RESEARCH ASSISTANTS:

Eugenia Chow	M.S., Civil Engineering, January 1990
Chris Mueller	Ph.D., Civil Engineering, May 1994*
Mohammad Salama	Ph.D., Civil Engineering, December 1991
Michael Wysockey	Ph.D., Civil Engineering, May 1994*

* Expected completion date

EMP/EMI TESTING AND ASSESSMENT
(Project No. 53)

by

J.T. Verdeyen, Professor of Electrical and Computer Engineering

PROBLEM STUDIED:

Tactical and strategic structures must be well shielded against EMI/EMP for communications, control and information processing. An optically addressed sensor is needed for fast time response (less than one nanosecond), good sensitivity (less than one volt), and minimal perturbation.

SUMMARY OF MOST IMPORTANT RESULTS:

In the field of electromagnetic pulse (EMP) testing, there exists a need for sensors, which can be addressed optically, capable of measuring the electric or magnetic fields produced. The chief advantage of an optically based system is that the sensor's response may be transmitted to a remote location free of extraneous pickup on conventional connecting cables. The optically-based sensor was to act as a linear device modulating the properties of the light traversing through it with a simple transfer function across a wide frequency band in response to the applied EMP fields.

Work performed utilized the electroabsorption in quantum well semiconductor structures based on AlGaAs as grown by metalloorganic chemical vapor deposition. A transmission device based on a separate confinement heterostructure laser design continuing a single quantum well and a step-like wave guiding index profile demonstrated efficient modulation when operated as a light absorber rather than as an emitter.

Observations of changes in the transmitted optical power through this device, as a function of the applied forward and/or reverse DC bias, demonstrated nearly linear transfer functions for a given operating wavelength. Measurable changes in transmission were also observed for relatively small changes in applied voltage ($\approx$ 100 μV), allowing for the possibility of sensors with high sensitivity. Investigation of the high frequency operation of the device showed a one-to-one correspondence in amplitude and phase between the applied RF voltage and the modulation of the transmitted optical power over a wide frequency range (> 1 GHz). Linear operation was observed for a dynamic range exceeding 75 dB of the applied RF power at 20 MHz.

Experiments that coupled receiving antennas to a modulator demonstrated the ability to measure an incident electric field of 24 V/m with a 400 MHz bandwidth and the corresponding time derivative of the magnetic field with a 40 MHz bandwidth. At 20 MHz, electric fields as small as 2 V/m were measured. A 24 dB dynamic range in the measured electric field was demonstrated, and an expected range of 75 dB would imply the ability to measure fields as large as 10^4 V/m.

The potential for wide bandwidth operation and linear response with respect to the applied voltage make these types of semiconductor structures attractive for EMP sensing as well as for other low power modulation applications.

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